Precision QCD at the LHC

NNPDF collaboration meeting
Gargnano, September 2023

Gavin Salam
Rudolf Peierls Centre for Theoretical Physics
& All Souls College, Oxford

Science and Technology Facilities Council
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European Research Council
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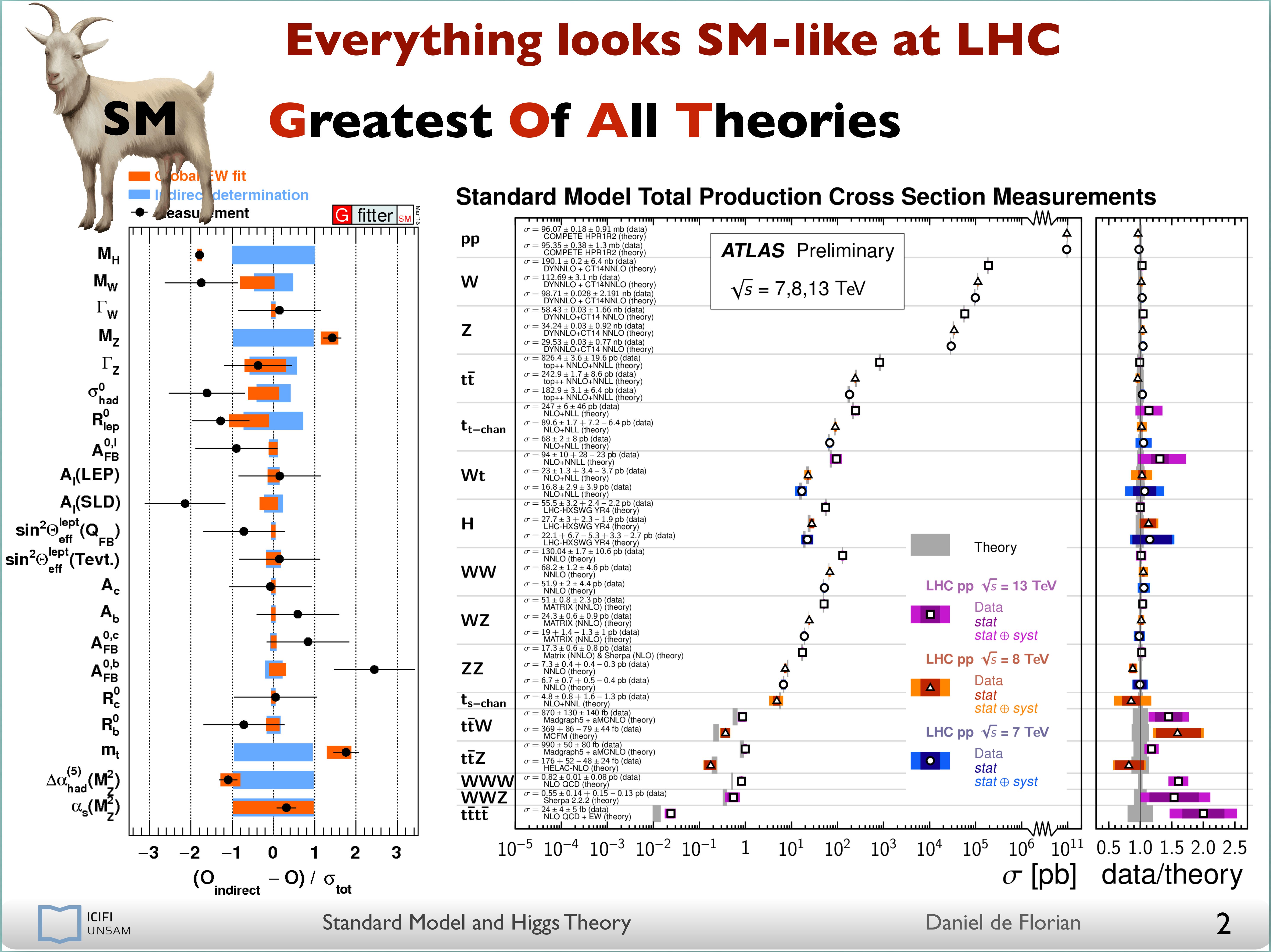
Success of the SM [de Florian @ EPS-HEP 2023]



particle physics

"big unanswered questions"

about fundamental particles & their interactions

(dark matter, matter-antimatter asymmetry,
nature of dark energy, hierarchy of scales…)

v.

"big answerable questions"

and how we go about answering them

(nature of Higgs interactions, validity of SM up to higher scales,
lepton flavour universality, pattern of neutrino mixing, …)

The Lagrangian and Higgs interactions: two out of three qualitatively new!

$$\mathscr{L}_{\rm SM} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

Gauge interactions, structurally like those in QED, QCD, EW, **studied for many decades** (but now with a scalar)

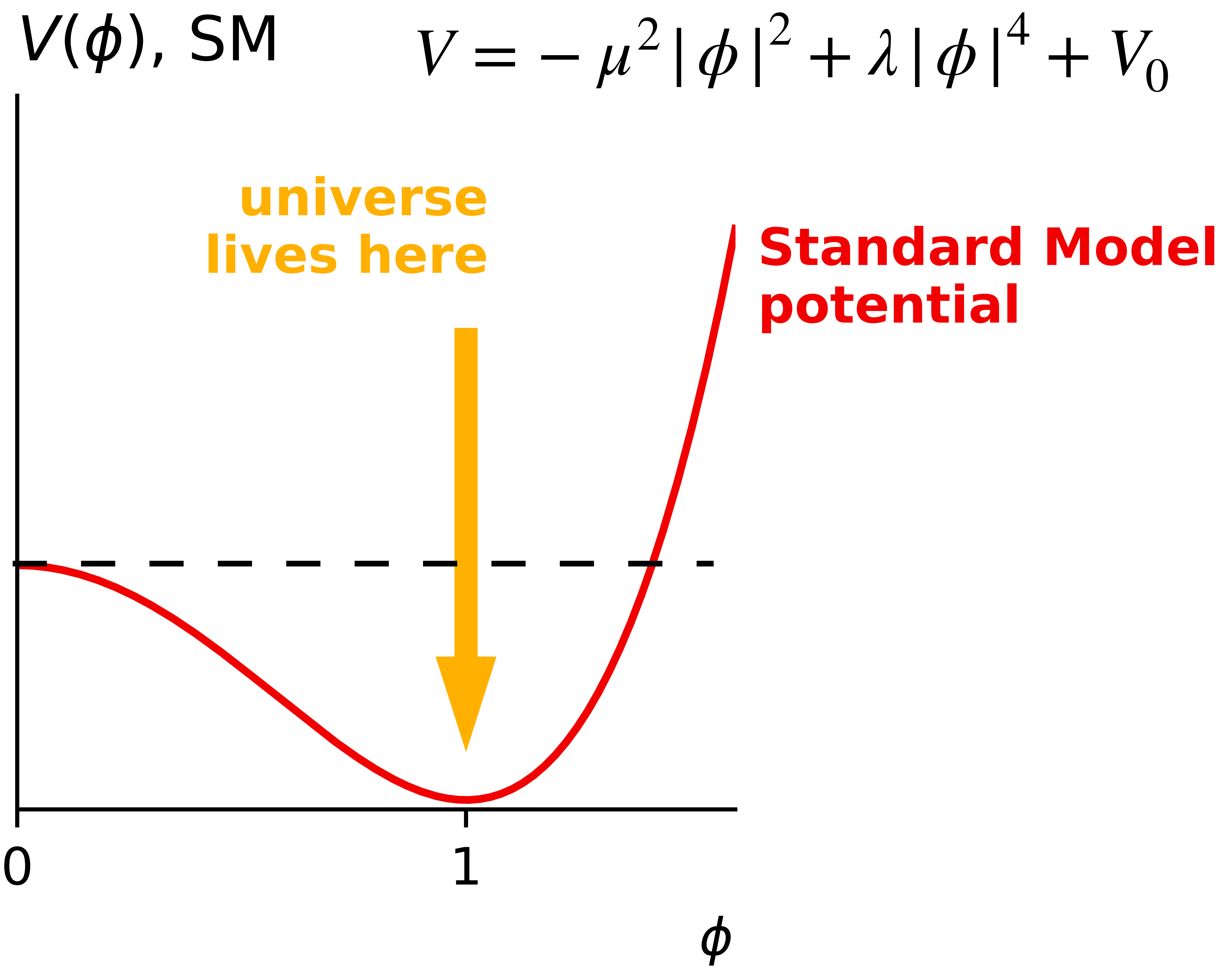
Yukawa interactions. Responsible for fermion masses, and induces “fifth force” between fermions. **Direct study started only in 2018!**

Higgs potential → self-interaction

Holds the SM together.

Unobserved

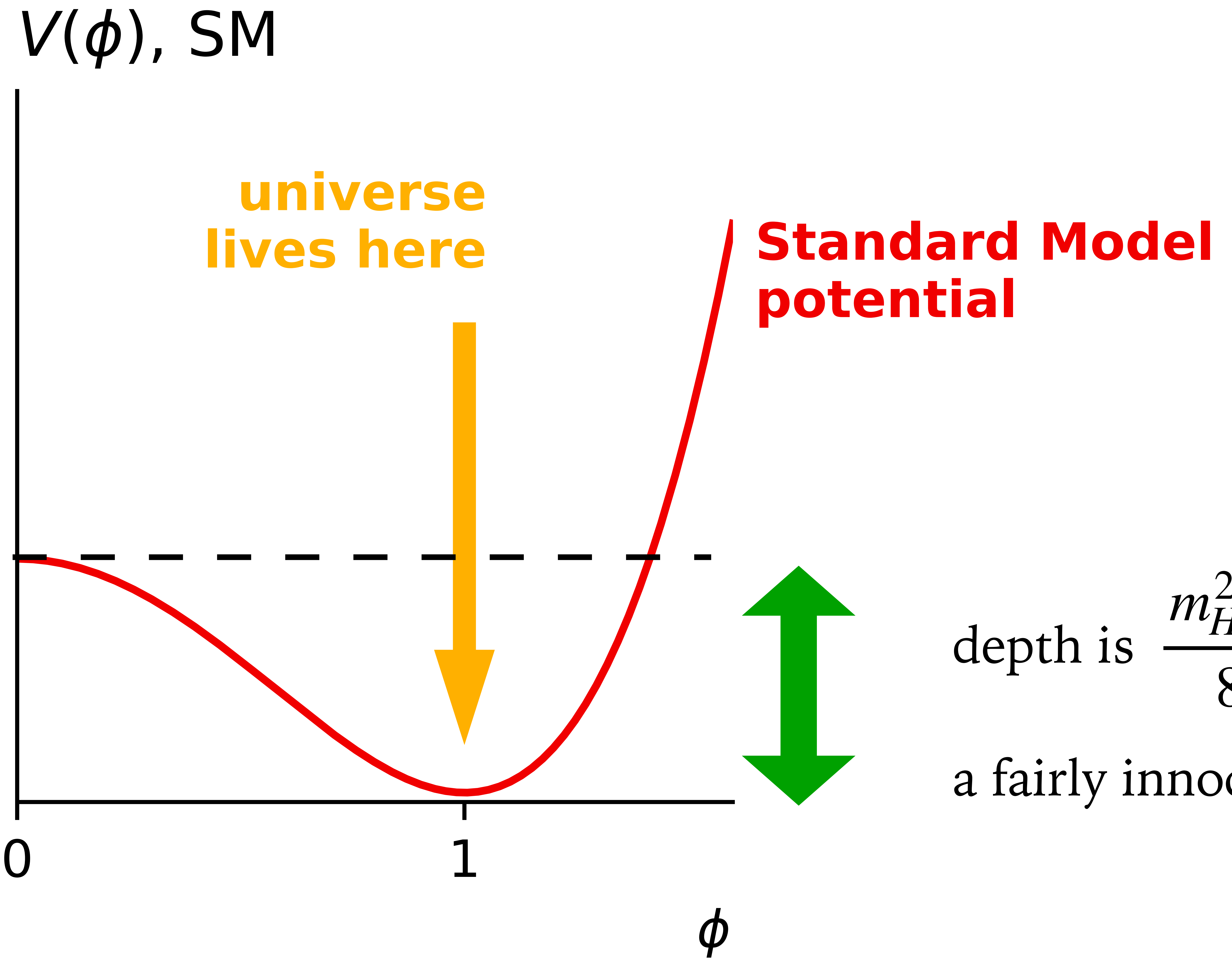
Higgs potential



Higgs mechanism gives mass to particles because Higgs field φ is non-zero

& that's because the minimum of the SM potential is at non-zero φ

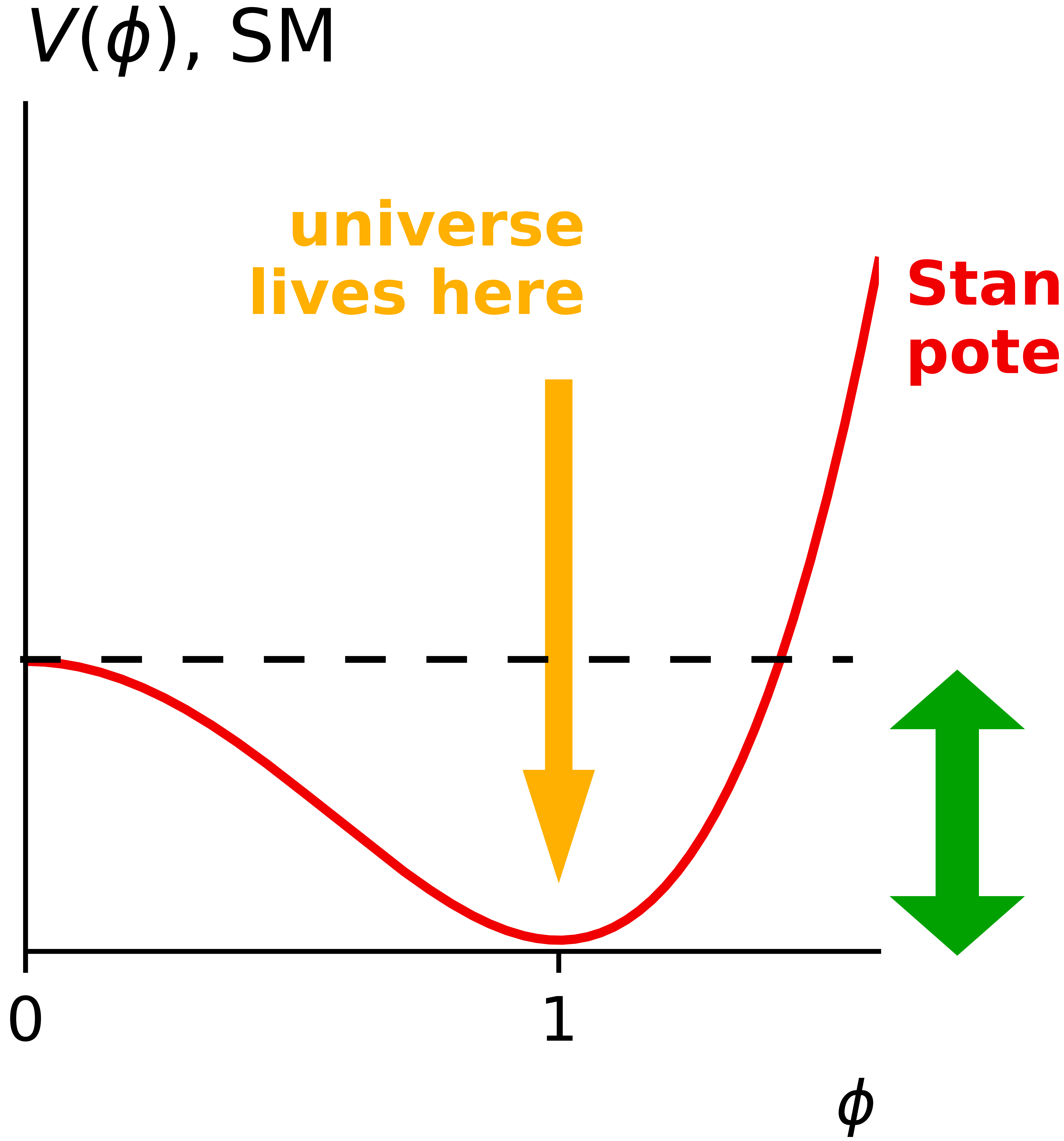
Higgs potential



depth is $\frac{m_H^2 v^2}{8}$ $(m_H \simeq 125\,\text{GeV},\ v \simeq 246\,\text{GeV})$

a fairly innocuous sounding $(104\,\text{GeV})^4$

Higgs potential – remember: it's an energy density



Corresponds to an energy density of
1.5×10^{10} GeV/fm^3
i.e. **10 billion times nuclear density**

Mass density of 2.6×10^{28} kg/m^3

What does 2.6×10^{28} kg/m^3 mean?

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By KMJ, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1443327

https://solarsystem.nasa.gov/resources/768/nasas-sdo-sees-sun-emit-mid-level-flare-oct-1/
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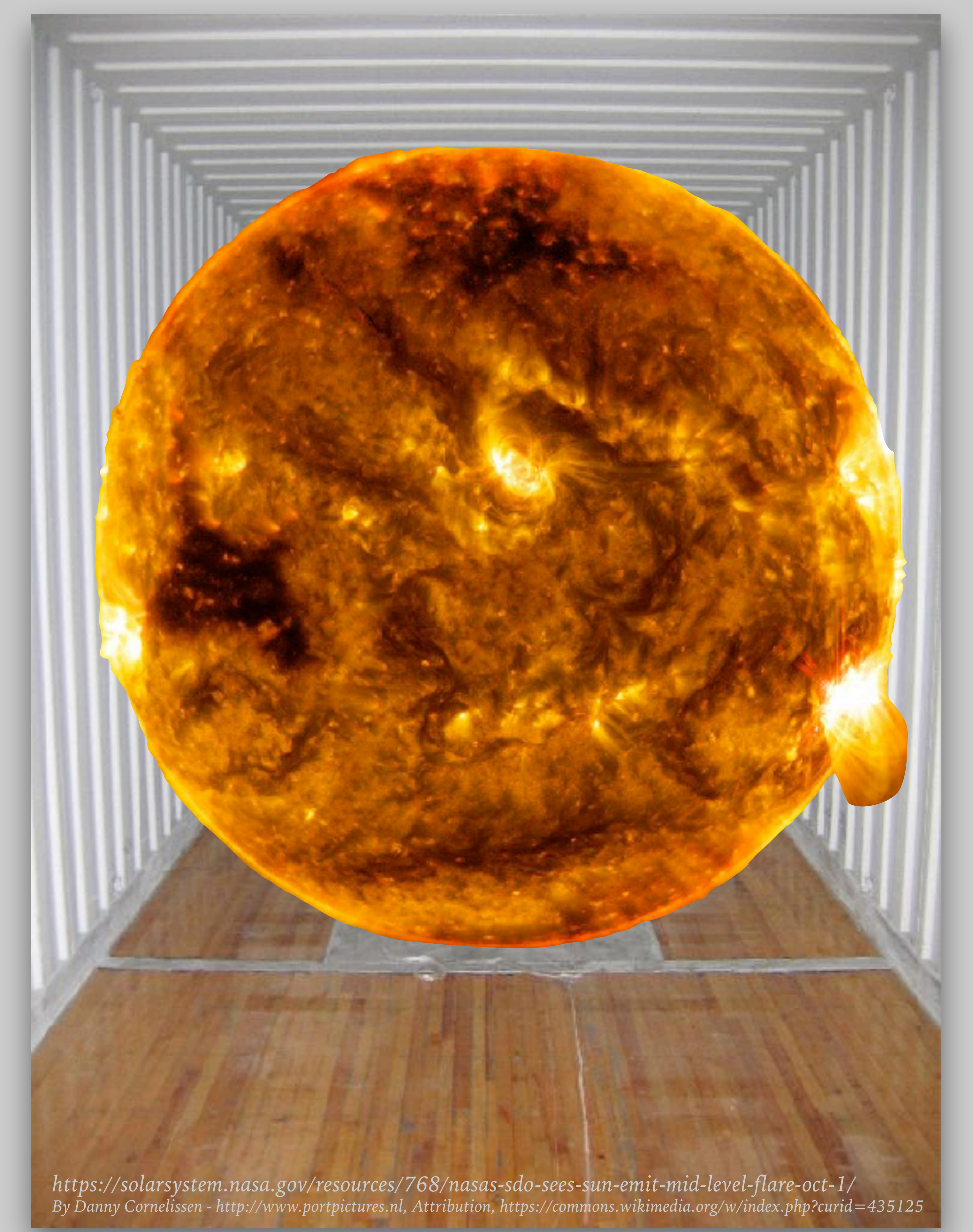
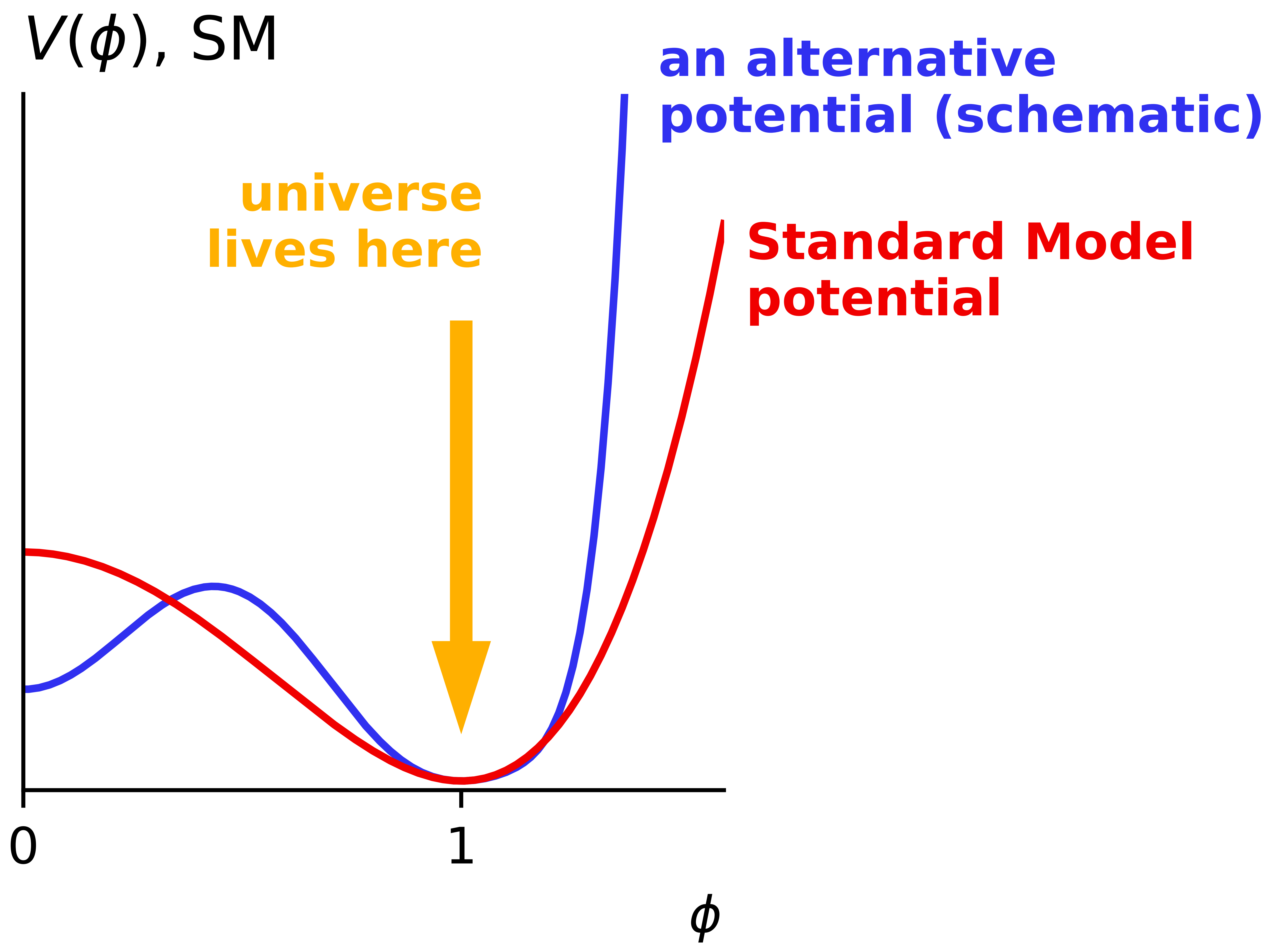
What does 2.6×10^{28} kg/m^3 mean?



fit the mass of the sun into a standard 40ft shipping container

Higgs potential — huge energy densities — yet to be experimentaly confirmed



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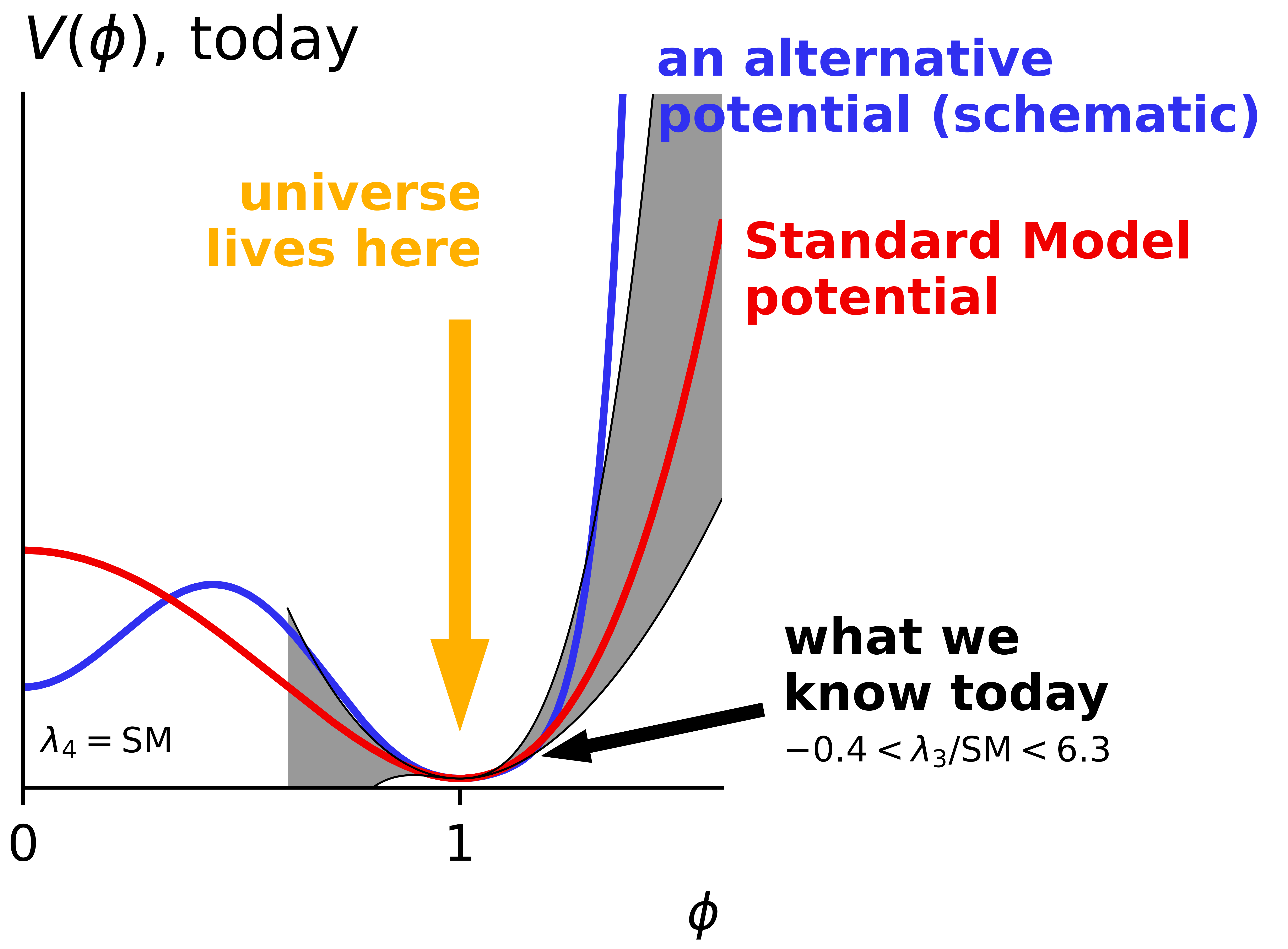

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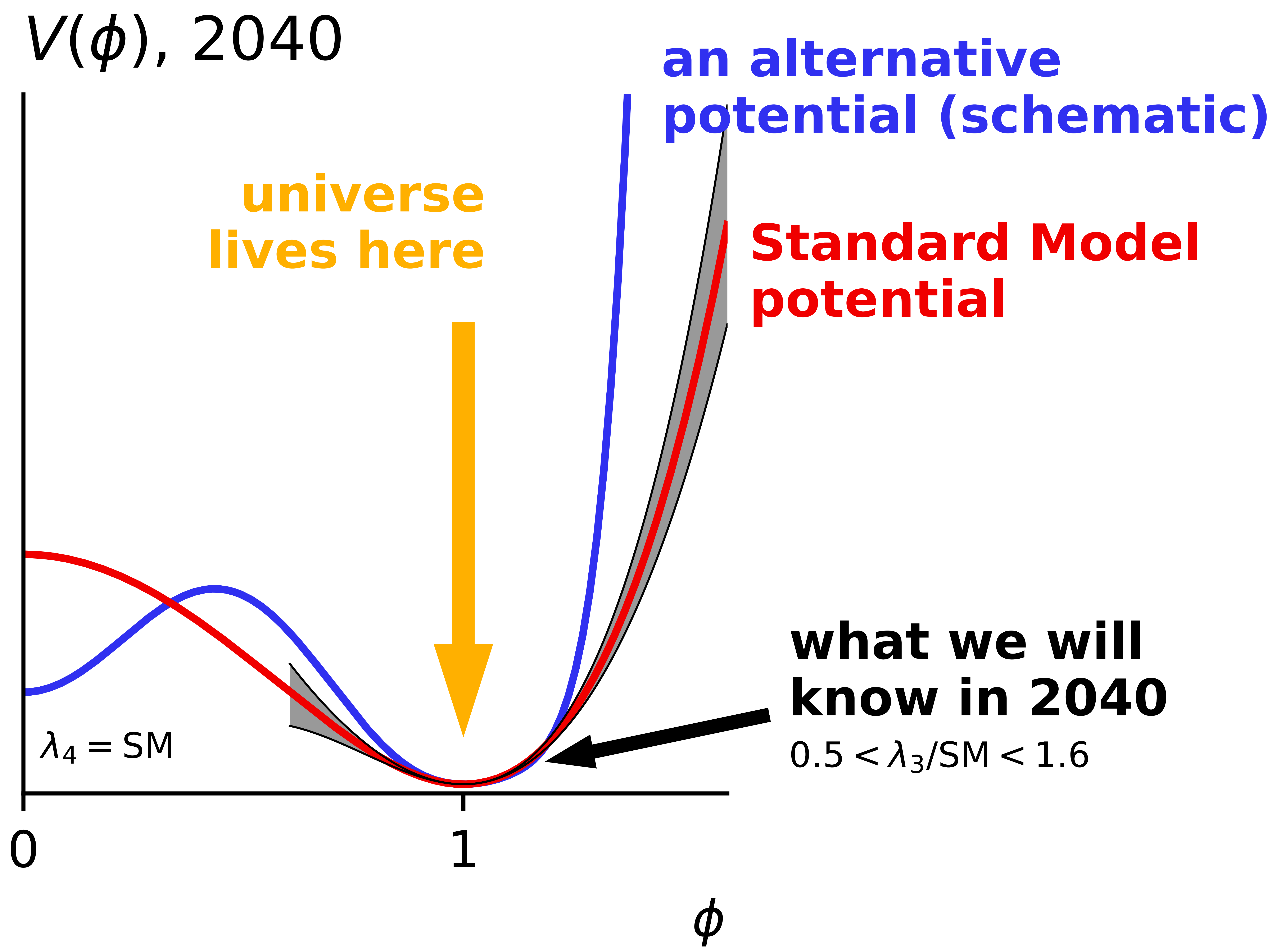

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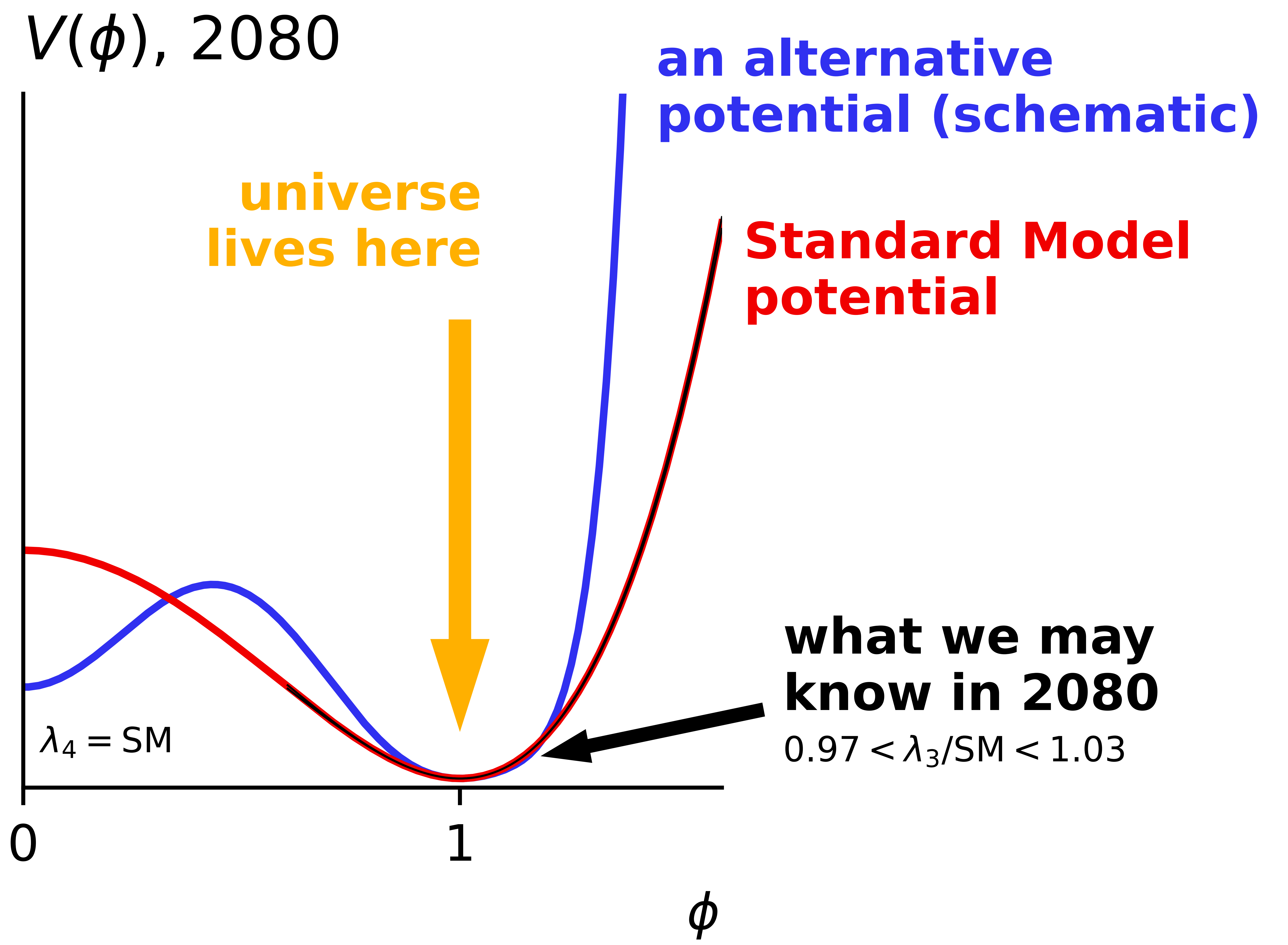
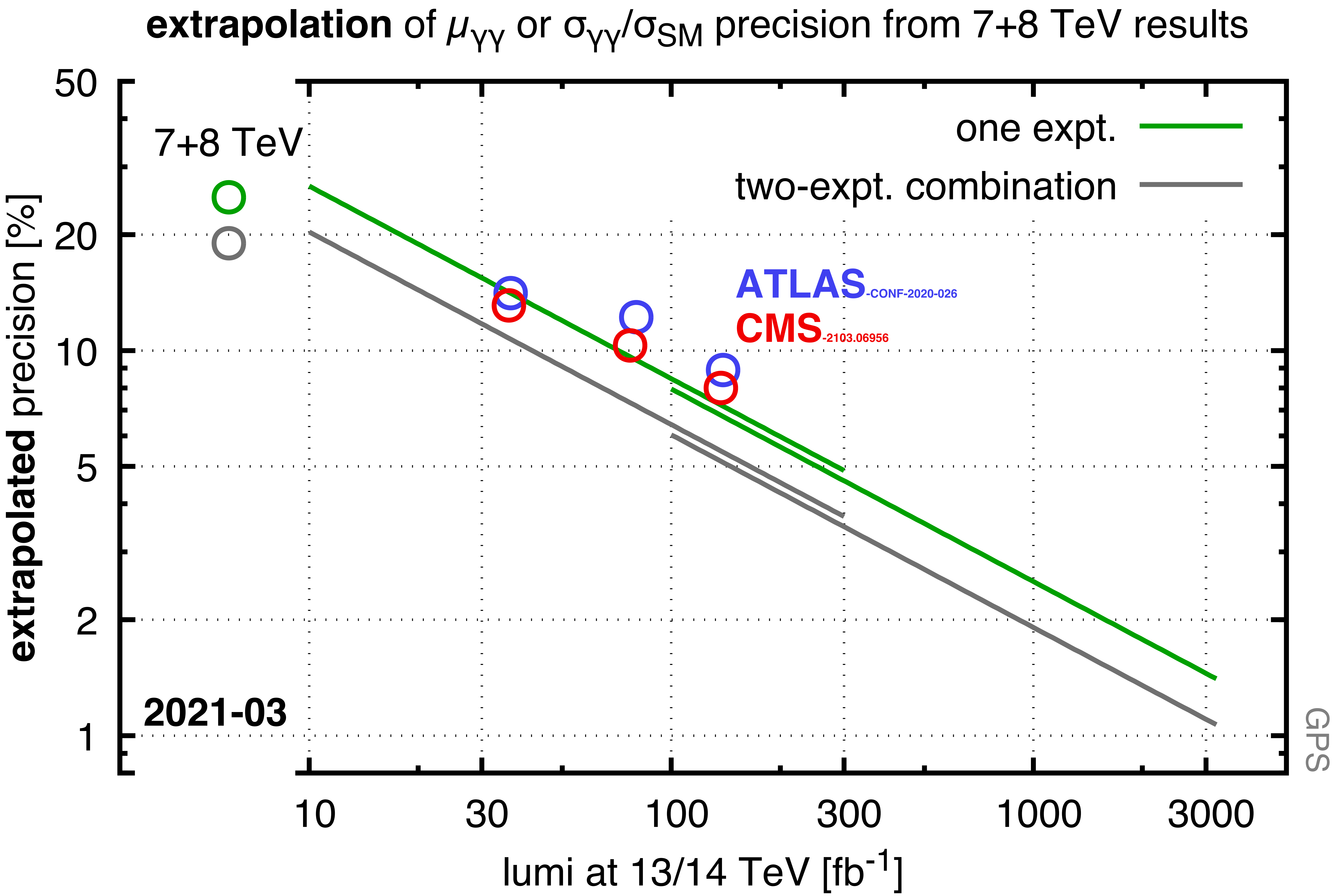


The LHC is increasingly a precision machine, even for Higgs physics



1% uncertainty on α_s
→ 2% uncertainty on
Higgs cross section

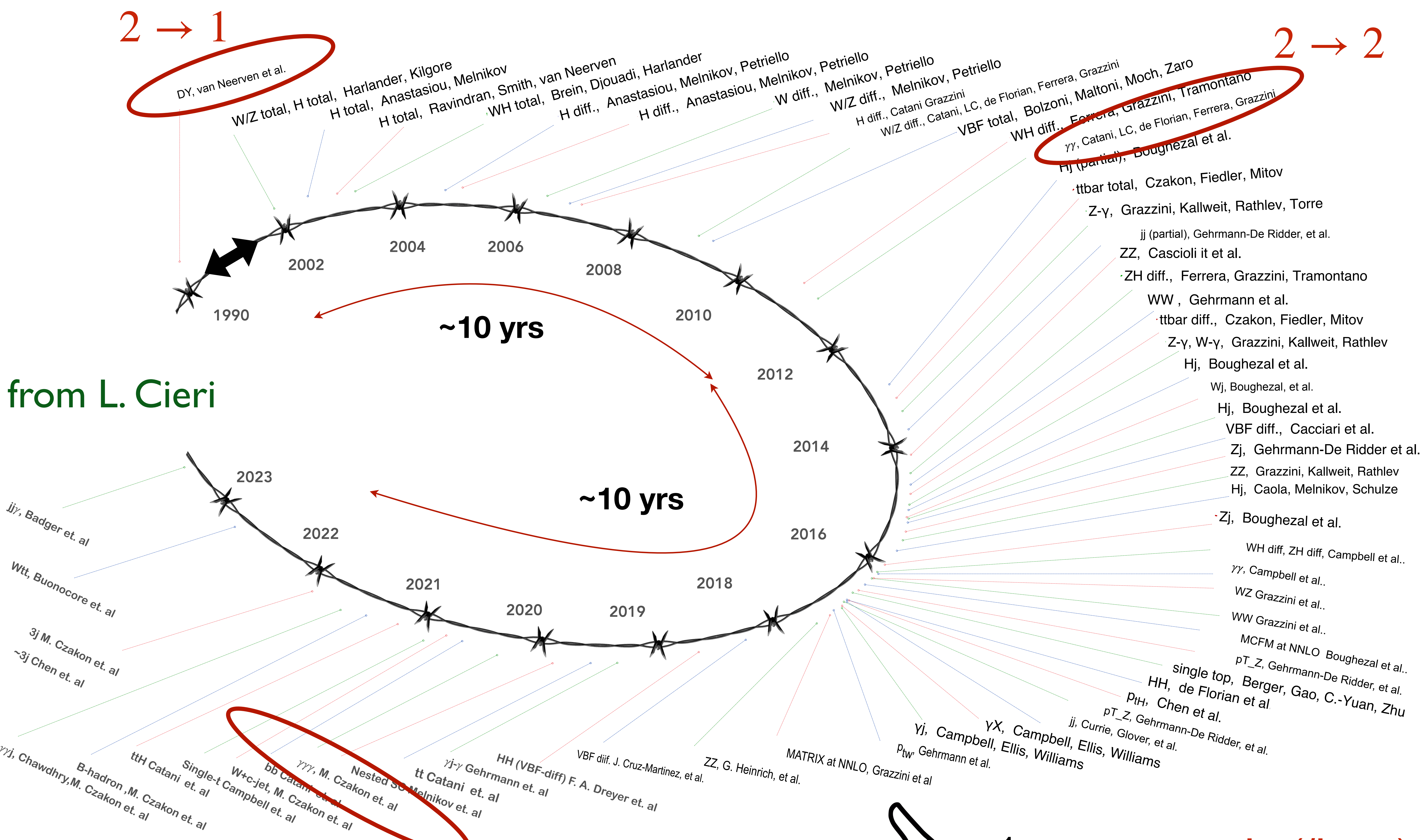
the master formula

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

the hard process

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

The NNLO ~~revolution~~ standard



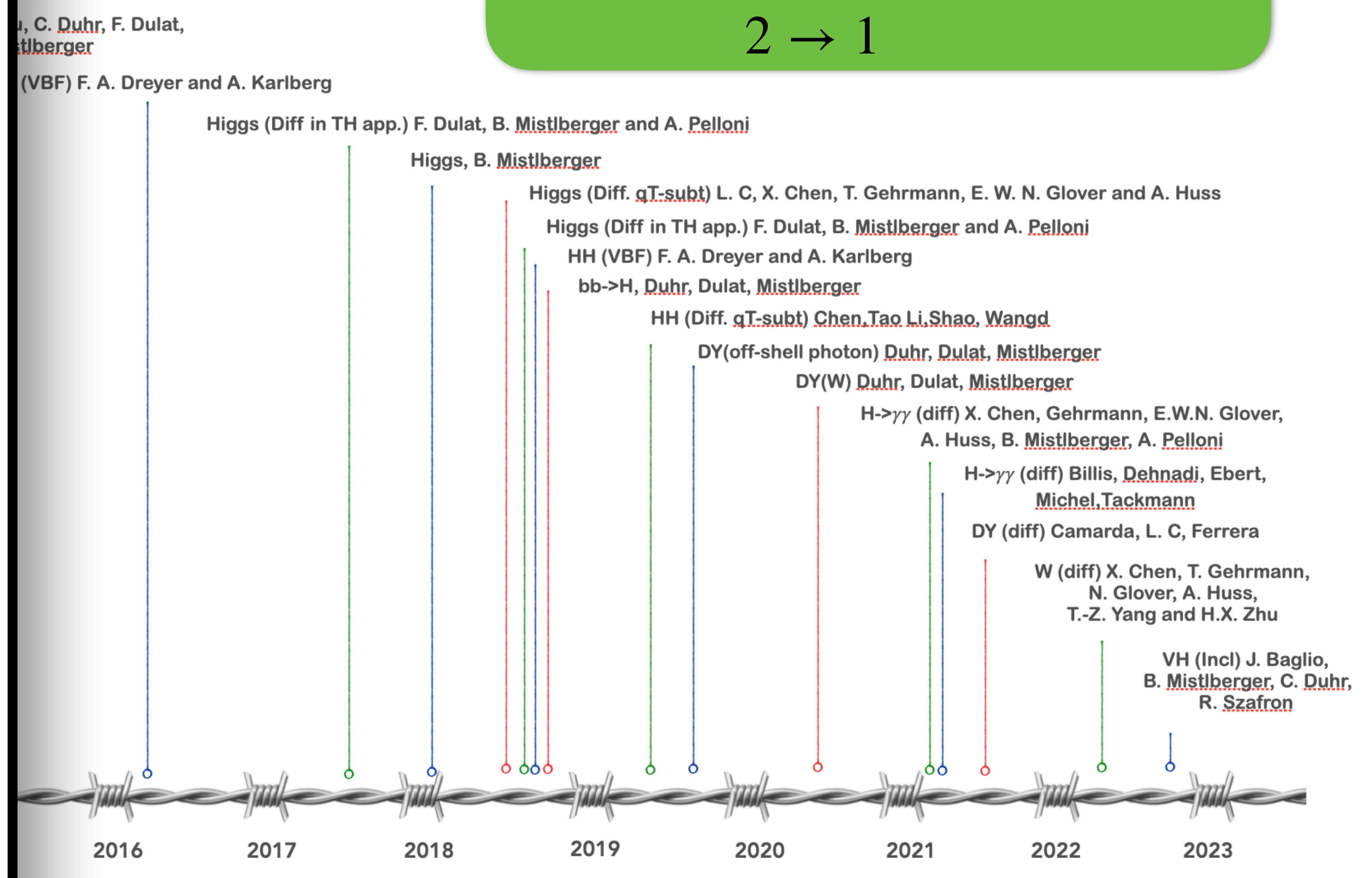
from L. Cieri

1 extra particle (/loop) every 10 years

[de Florian @ EPS-HEP 2023]

The N3LO revolution

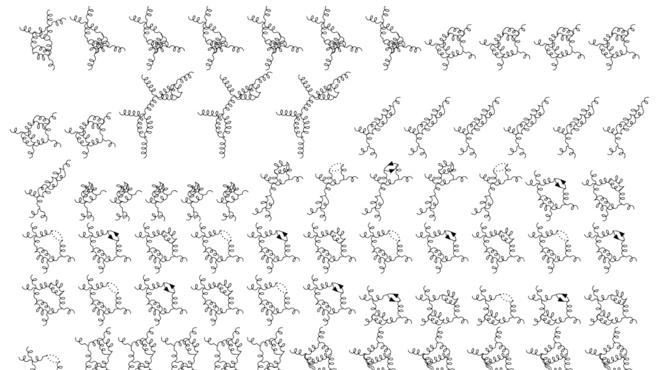
DY-like (no color in final state) 2 → 1



from L. Cieri

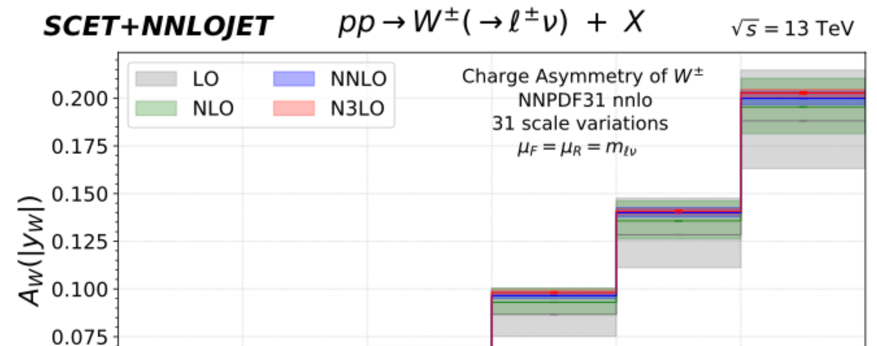
N3LO for processes with “2 final state particles”?

3 loop amplitudes for $pp \to jj$



Caola, Chakraborty, Gambuti, von Manteuffel, Tancredi (2022)

W transverse mass and charge asymmetry @N3LO



Chen, Gehrmann, Glover, Huss, Yang, Zhu (2022)
q_T subtraction

- flat for rapidity distribution, about -2.5%

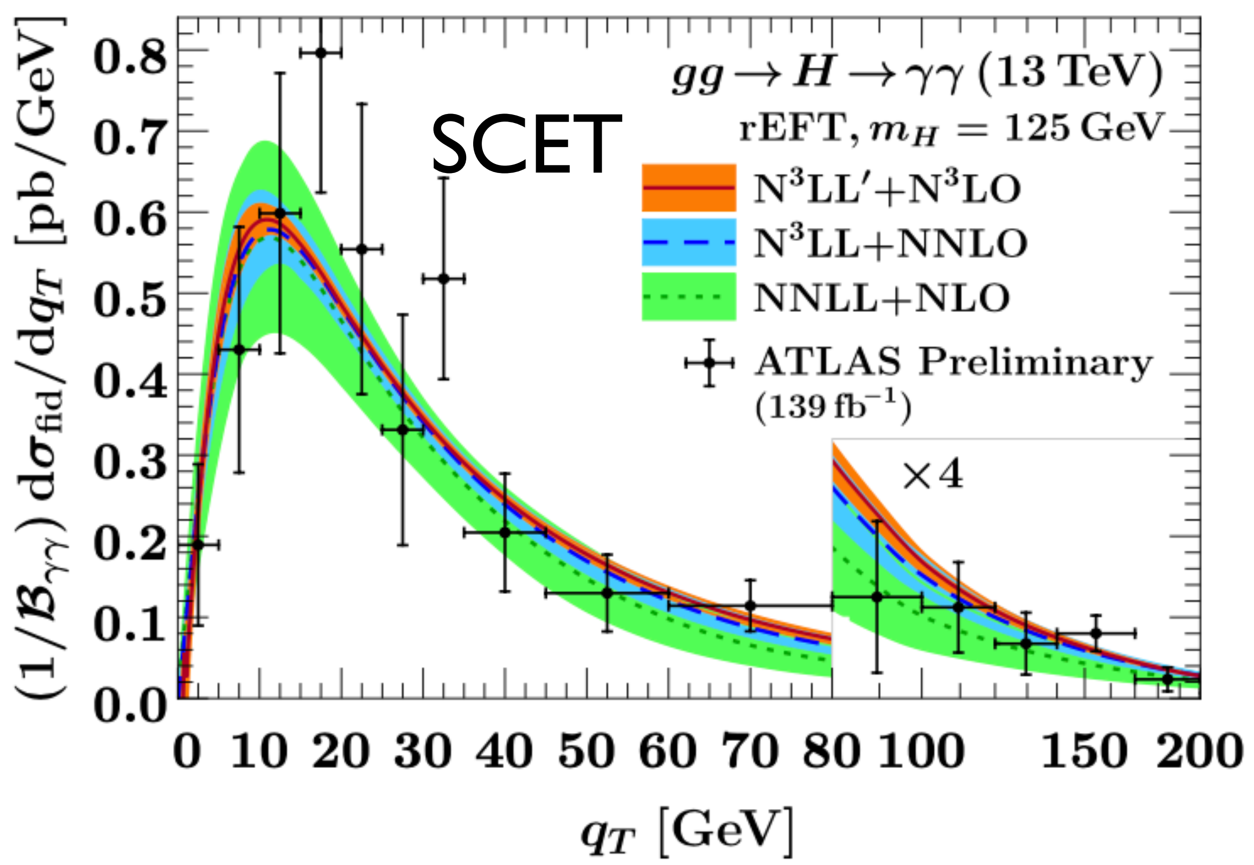
Charge asymmetry relevant for pdfs

[de Florian @ EPS-HEP 2023]

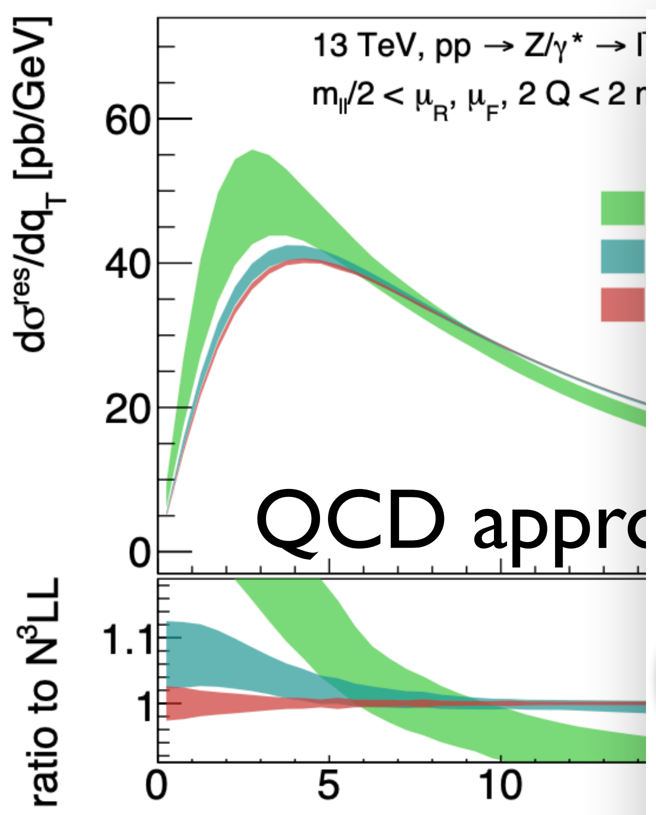
Resummation: state of the art for q_T resummation

- In the boundaries of phase space → soft and collinear emission

Large logs appear → spoil convergence of expansion in $\alpha_s^n \log^{2n} \frac{q_t}{Q}$



Billis, Denhadi, Ebert, Michel, Tackmann(2021)



Camarda, Cier

N3LL' resummation + N3LO   N3LL resum

- Provide fiducial cross sections improved by q_T resummat
- Nice convergence and typically *O(%)* corrections wrt pre

Parton Shower accuracy

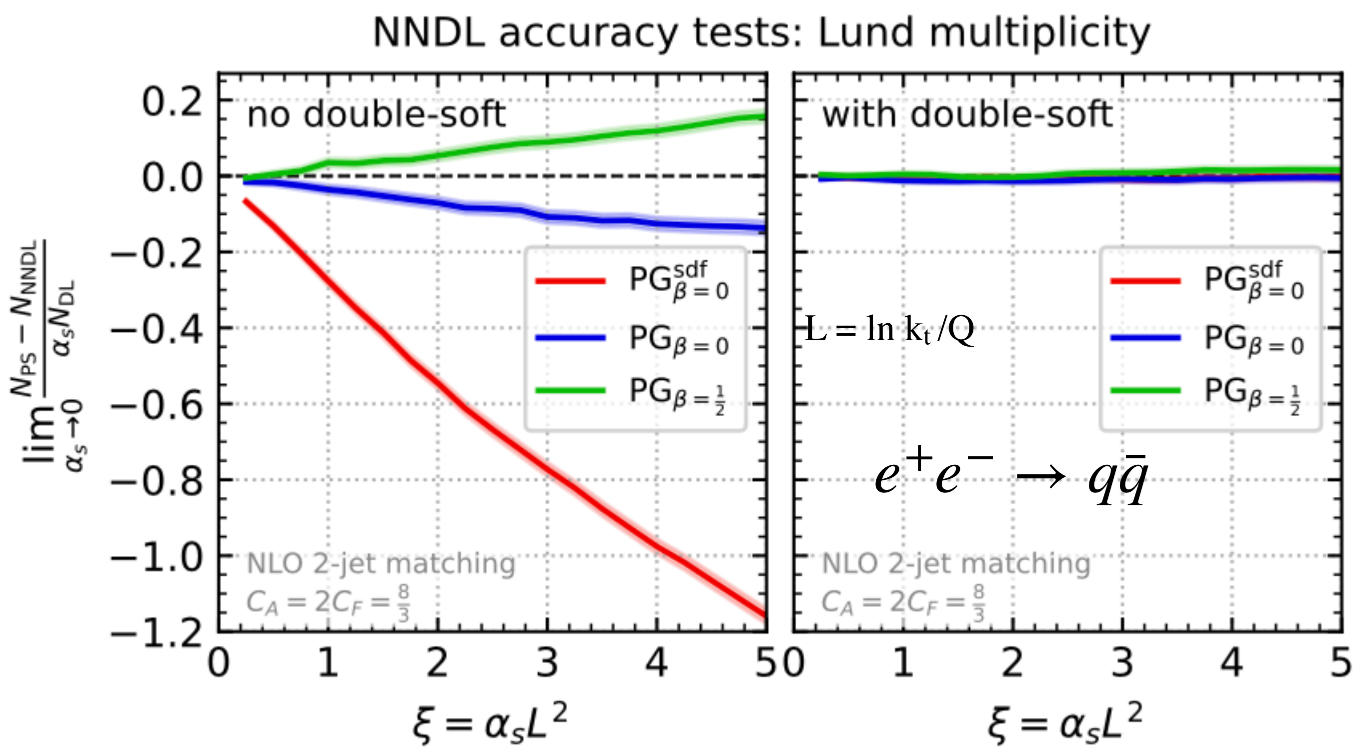
- PS is a core component of MC simulation: used in almost every analysis
- Standard parton showers are LL(+) accurate: limitation for precision

Dasgupta, Dreyer, Hamilton, Monni, Salam (2018)

- Several groups producing new generation of NLL PS for general observables

Nagy-Soper, Holguin-Forshaw-Platzer, PanScales, Herren-Höche-Krauss-Reichelt-Schönherr + …

- NEW: various attempts towards even higher accuracy NNLL



PanScales: Ravasio, Hamilton, Karlberg, Salam, Scyboz, Soyez (2023)

- kinematics of the recoil
- color structure
- virtual contributions
- triple collinear
- double soft

Inclusion of double soft reproduces analytical results at order $\alpha_s^n L^{2n-2}$

PDFs

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

PDFs

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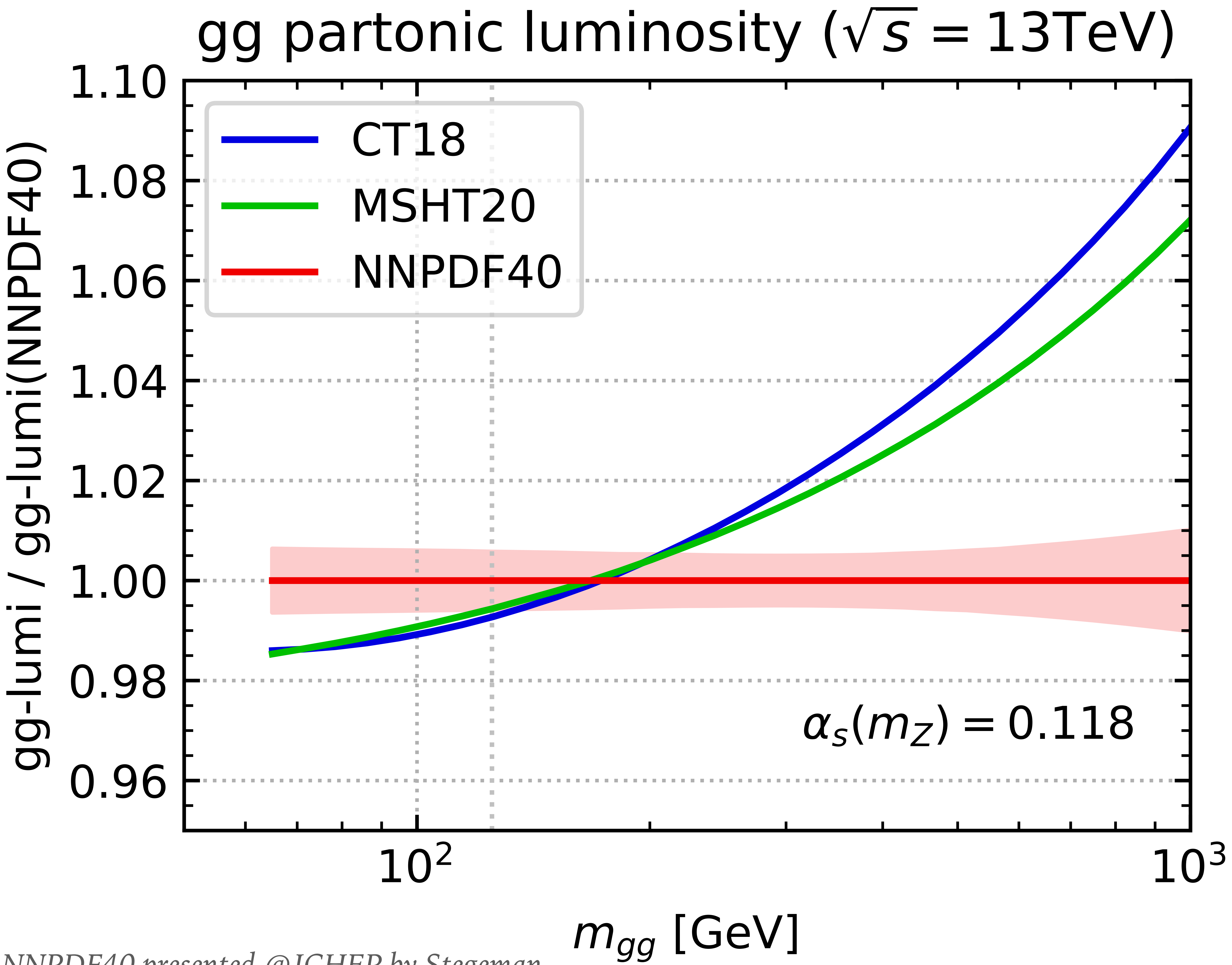
Comparing modern PDF sets



NNPDF40 presented @ICHEP by Stegeman

NB: PDF4LHC21 uses CT18/MSHT20/NNPDF31

gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	1.0000	±	0.0184
PDF4LHC21	0.9930	±	0.0155
CT18	0.9914	±	0.0180
MSHT20	0.9930	±	0.0108
NNPDF40	0.9986	±	0.0058

×3

Amazing that MSHT20 & NNPDF40 are reaching %-level precision

Differences include

- methodology (replicas & NN fits, tolerance factors, etc.)
- data inputs
- treatment of charm

At this level, QED effects probably no longer optional (MSHT20QED: 0.9870)

α_s from Z p_T

Table 1: Summary of the uncertainties for the determination of $\alpha_s(m_Z)$.

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

Default PDF is MSHT20(aN3LO), gives 0.11828

Table 2: Summary of N^{3}LL fits with NNLO PDFs.

PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]	χ^2/dof
MSHT20 [32]	0.11839	0.00040	0.44	-0.07	96.0 /69
NNPDF40 [78]	0.11779	0.00024	0.50	-0.08	116.0/69
CT18A [79]	0.11982	0.00050	0.36	-0.03	97.7 /69
HERAPDF20 [63]	0.11890	0.00027	0.40	-0.04	132.3/69

Difference of 0.00143, significantly larger than quoted ~0.00086 error

W mass

Table 2: Overview of fitted values of the W boson mass for different PDF sets. The reported uncertainties are the total uncertainties.

PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$

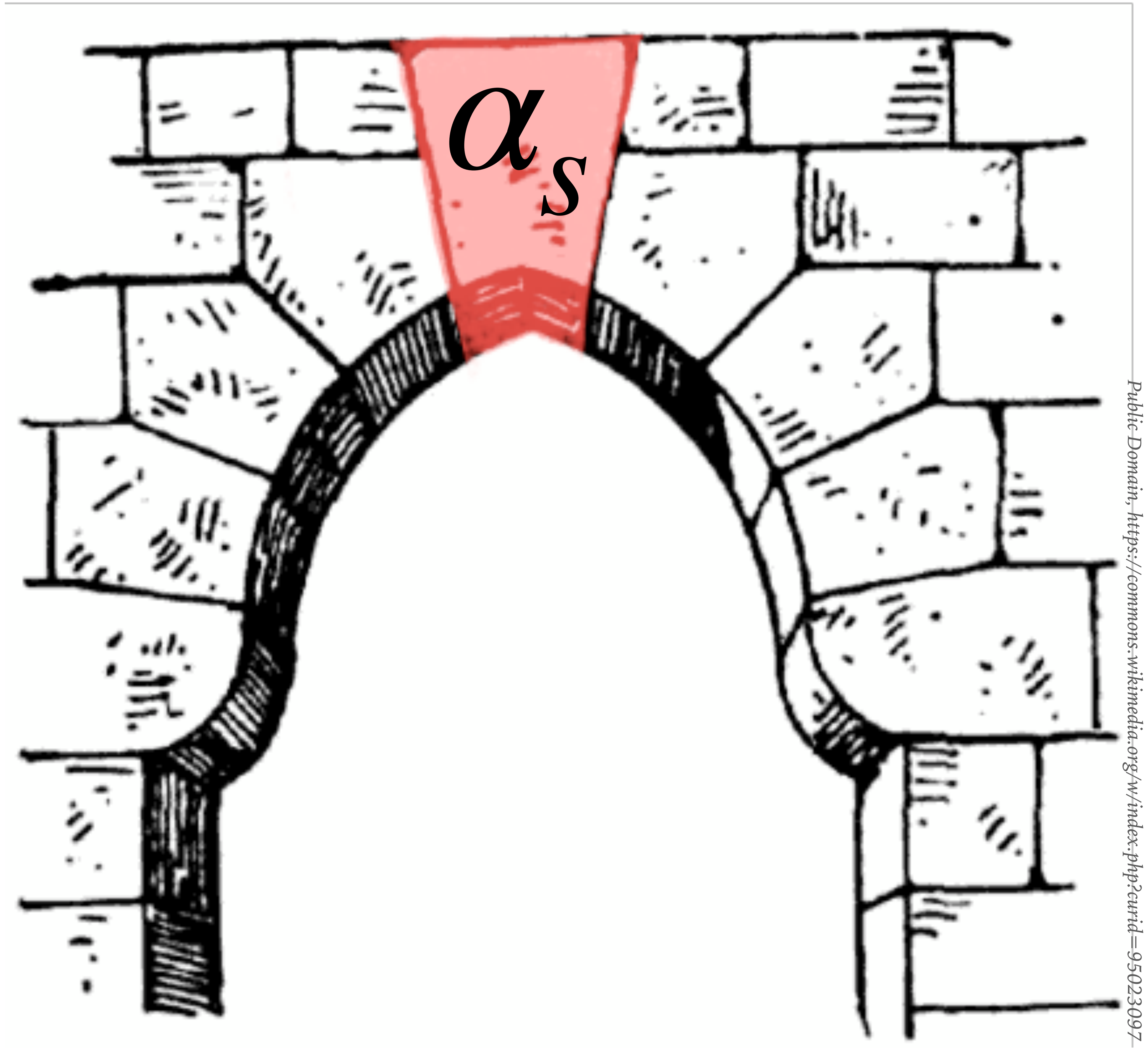
default

Difference of 17.9 MeV, greater than final quoted 16.3 MeV error

Is there a single PDF that is the "right one"?
Choice ≡ systematic error…
Should it not be the same across analyses?
(W mass relies profoundly on same Z p_T distribution that goes into α_s extraction)

the non-perturbative part

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$



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the strong coupling

HD-PY 92/13
OPAL-CR093
October 23, 1992

TESTS OF QCD *

Siegfried Bethke §
Physikalisches Institut, University of Heidelberg
Philosophenweg 12
D-6900 Heidelberg, Germany

The final world average is thus quoted to be

$$\boxed{\alpha_s(M_{Z^0}) = 0.118 \pm 0.007},$$

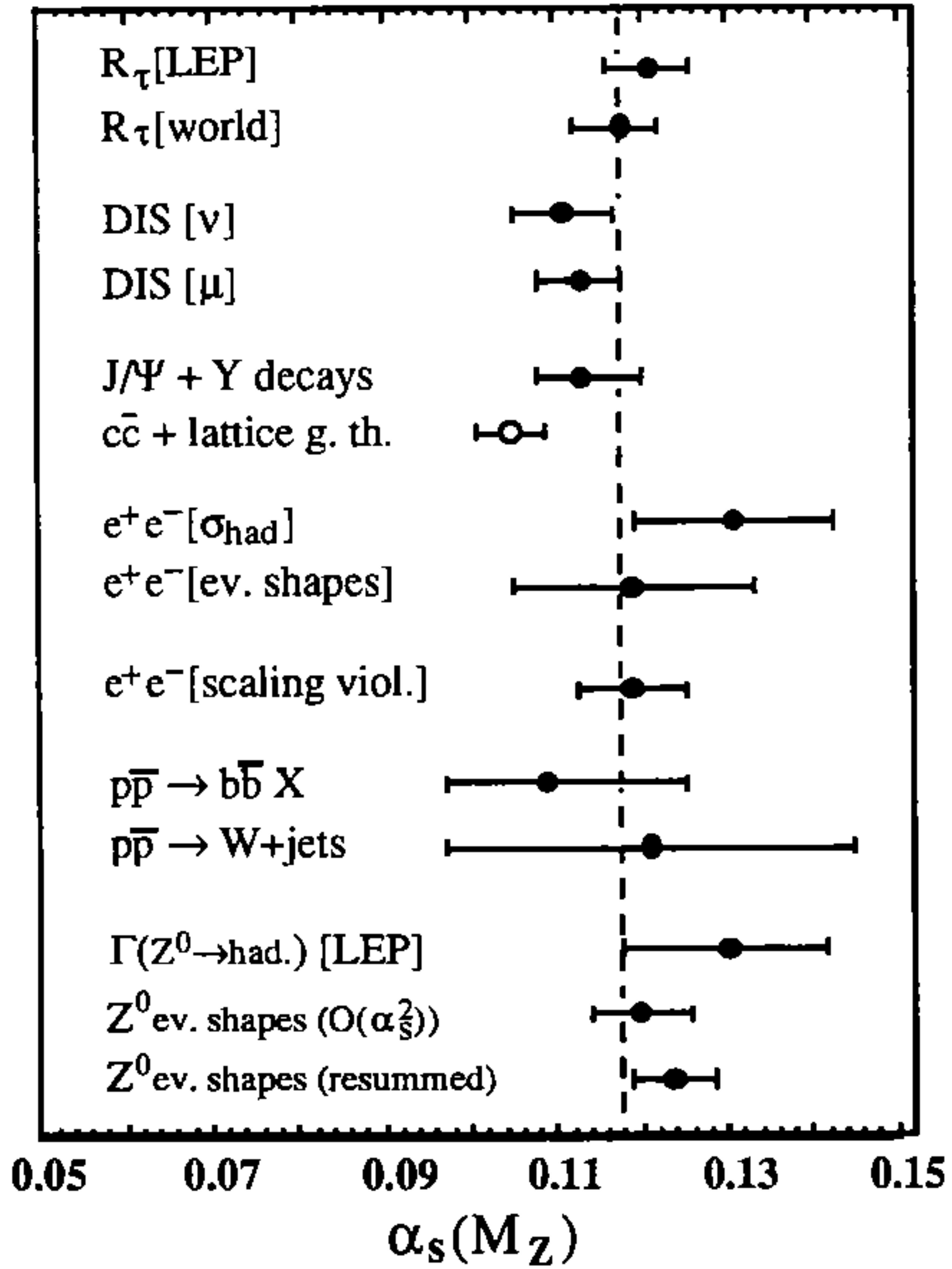


Fig. 31. Summary of measurements of $\alpha_s(M_{Z^0})$.

Three decades of the strong coupling

Uncertainty has gone down by an order of magnitude to ~ 0.8%

central value has stayed stable, today

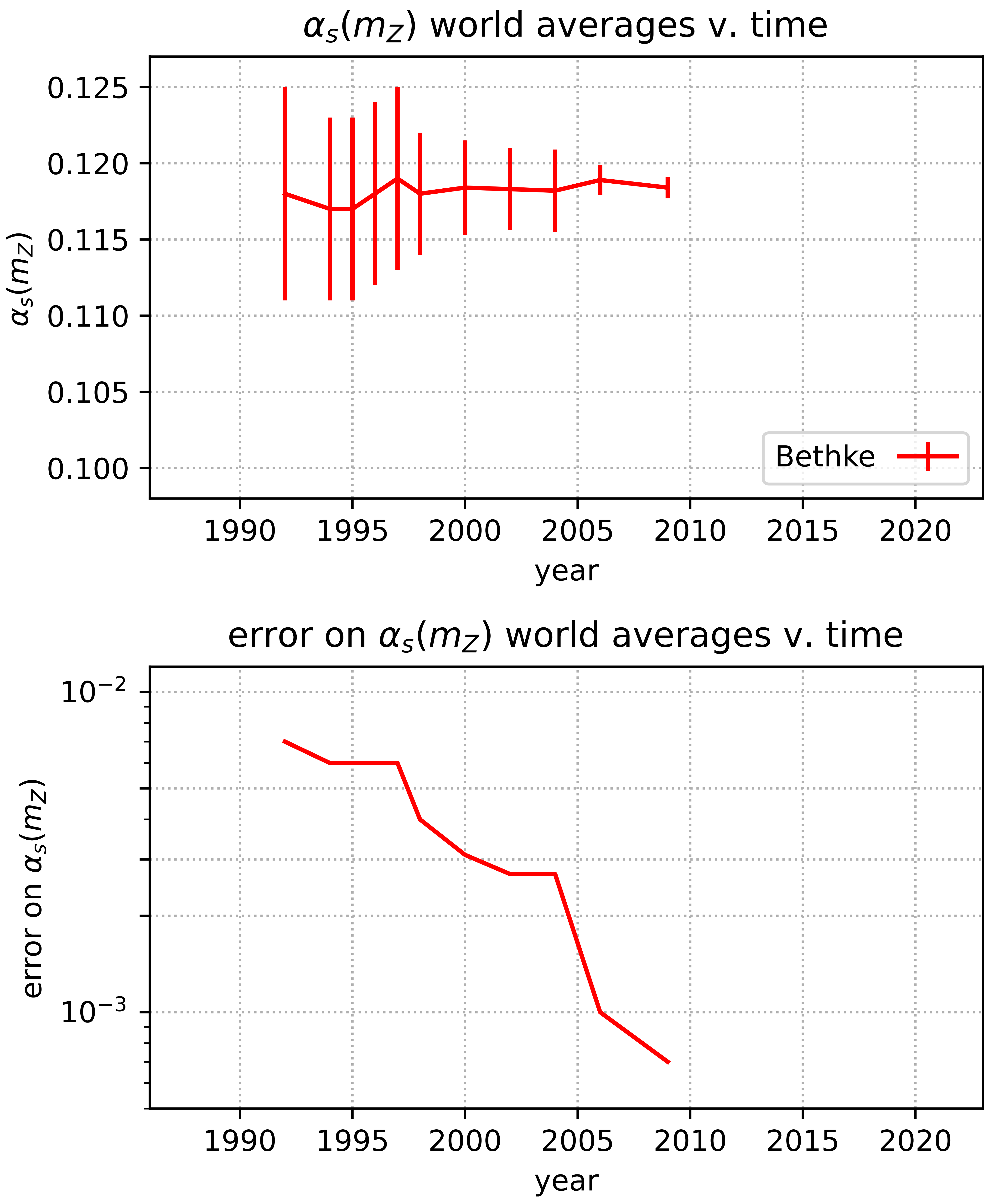
$\alpha_s(m_Z) = 0.1179 \pm 0.0009$

Sources of improvement

- data (LEP, DIS,~LHC)
- better theory (e.g. NNLO, N3LL)
- better computers (e.g. for lattice)

Challenges

- how to handle spread of error estimates (e.g. when systematic dominated)



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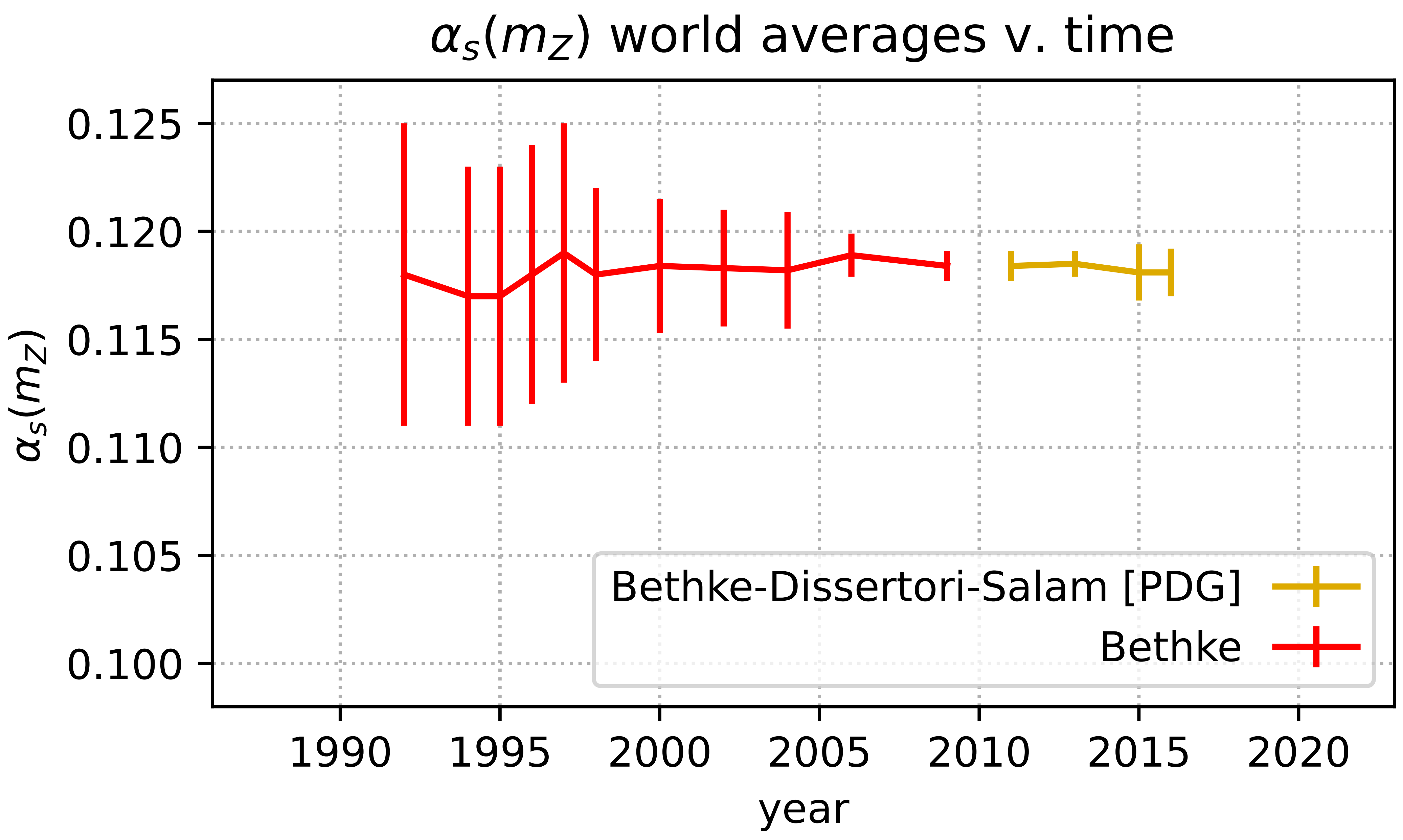

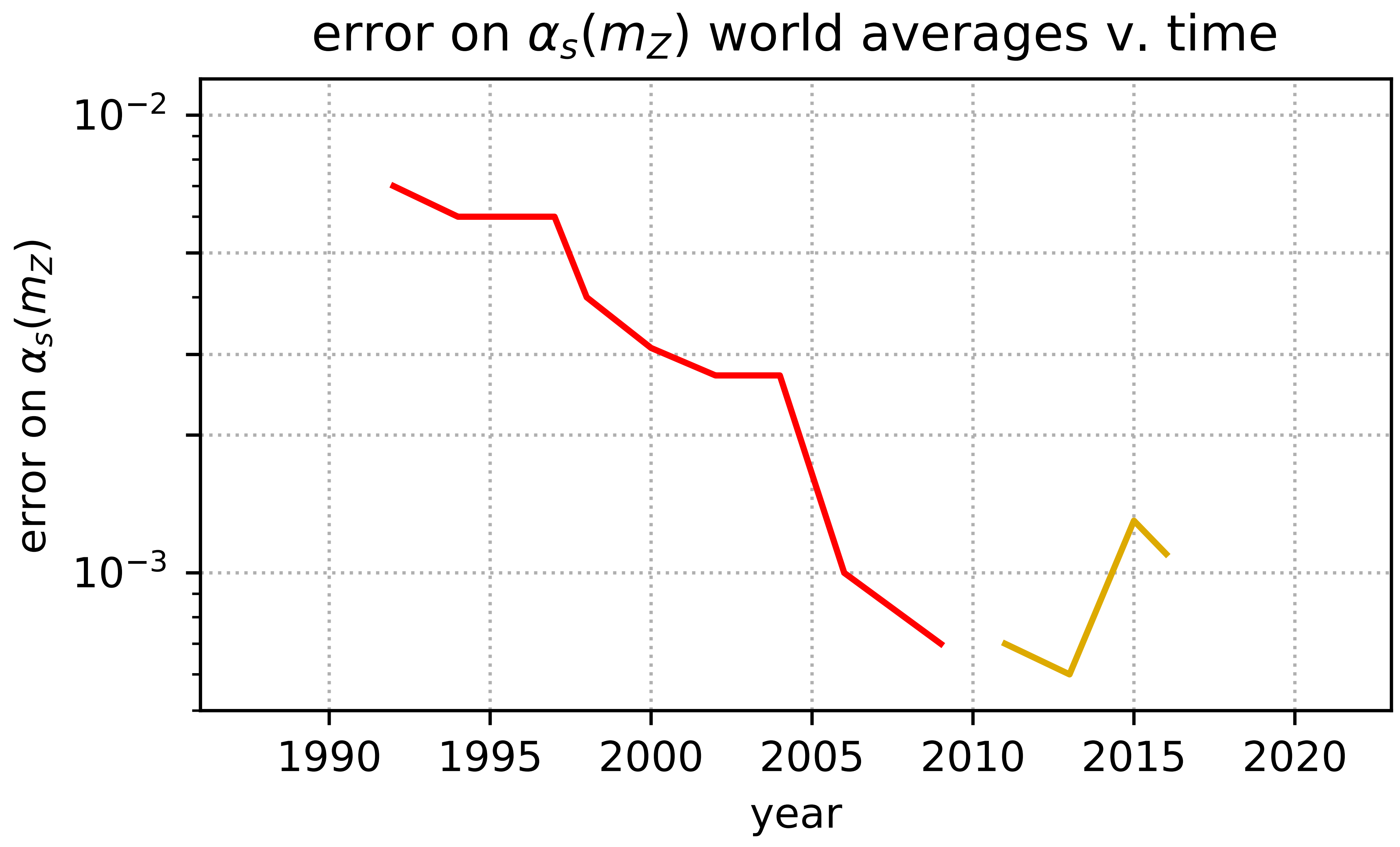

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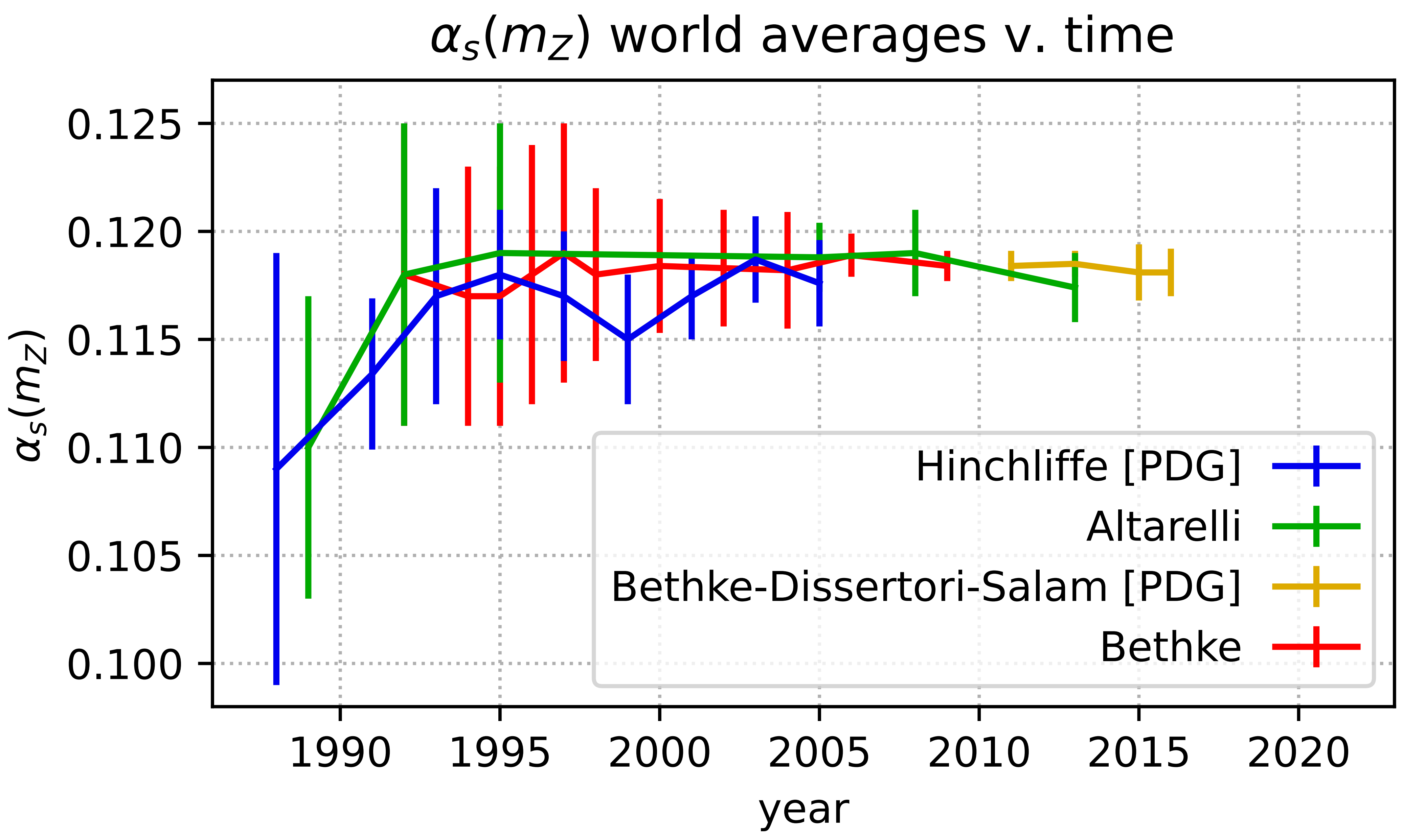

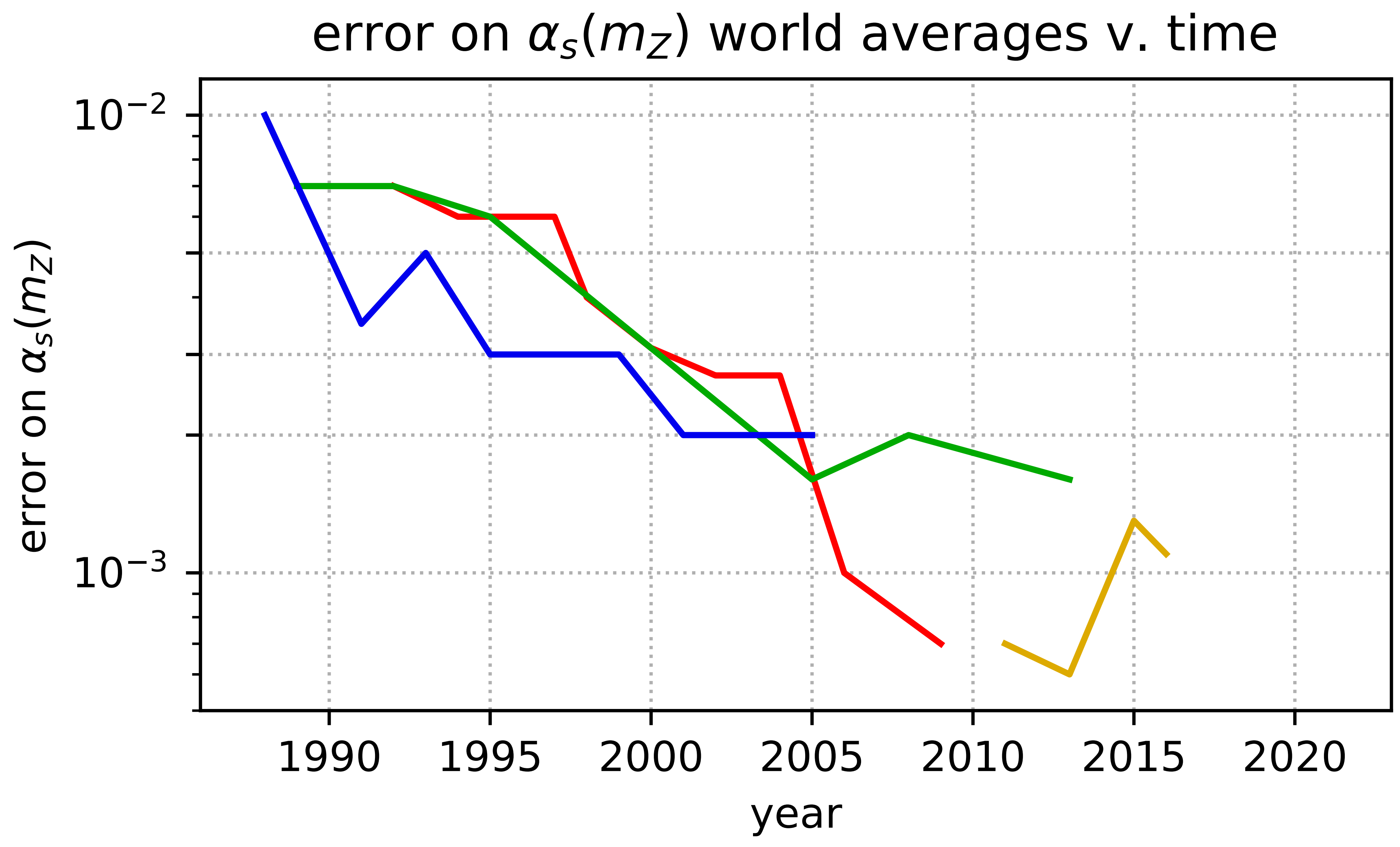

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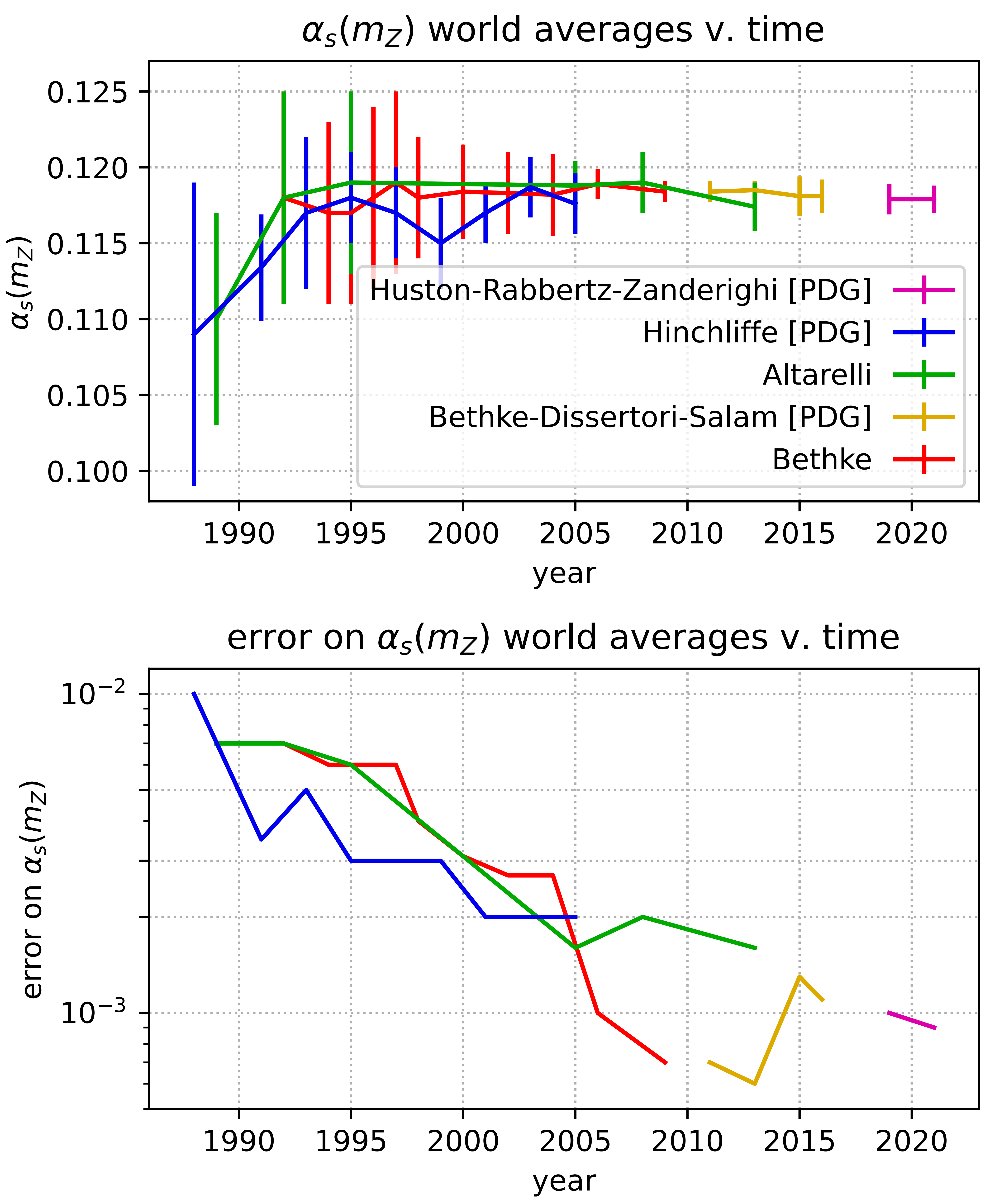


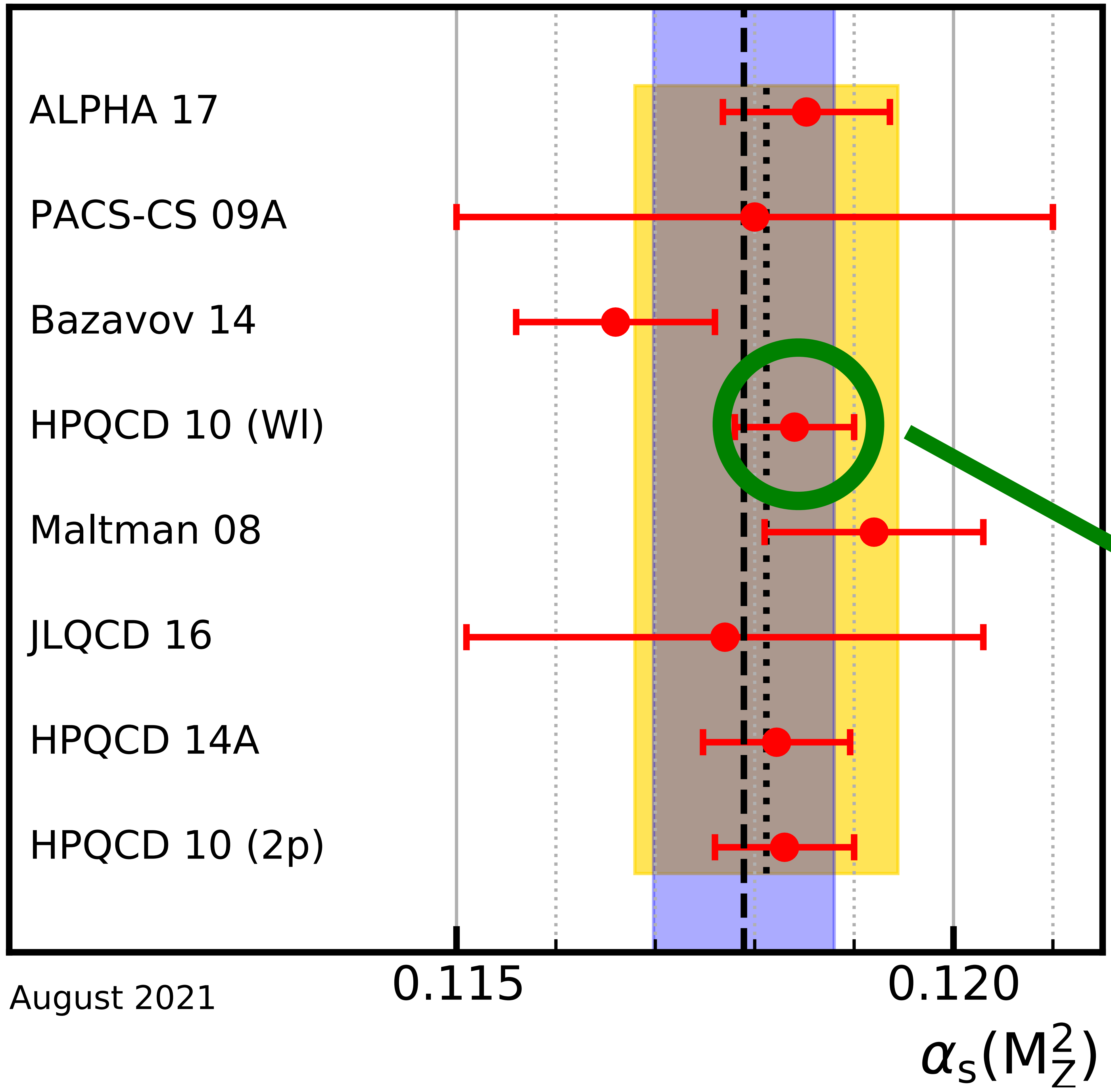
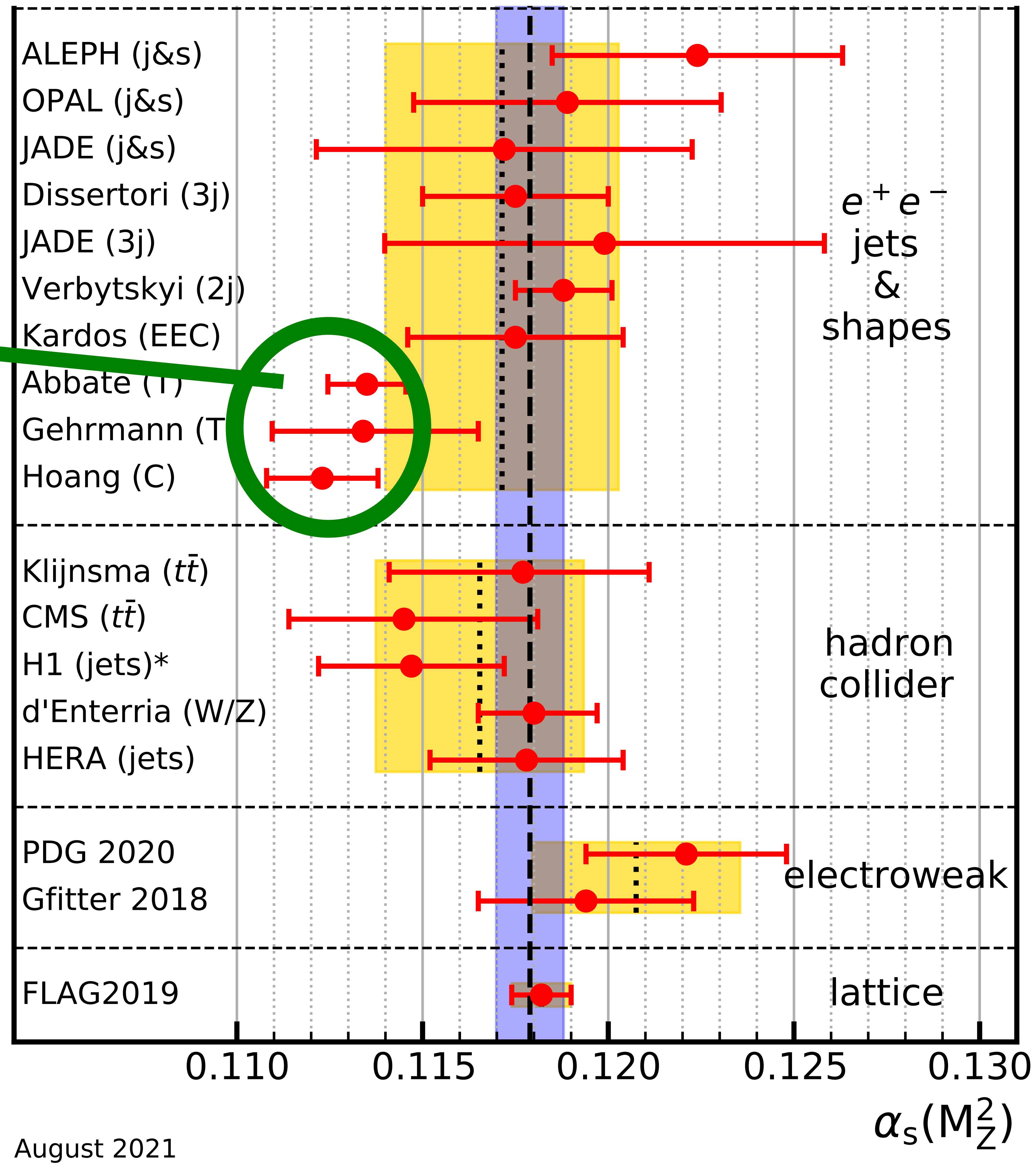
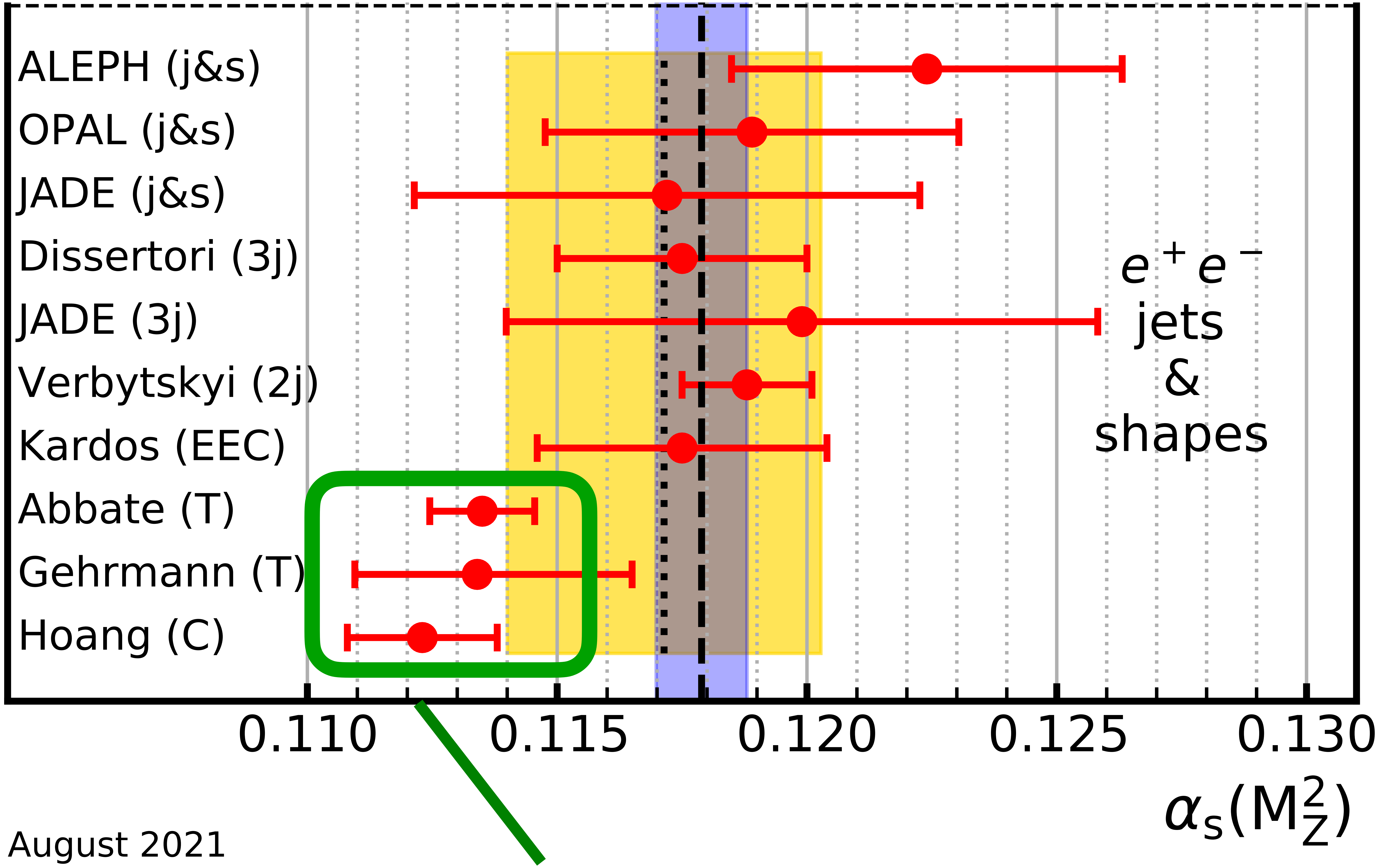


Figure 9.5: Lattice determinations that enter the FLAG2019 average. The yellow (light shaded) band and dotted line indicates the average value for this sub-field. The dashed line and blue (dark shaded) band represent the final world average value of $\alpha_s(M_Z^2)$. [a]

outliers and/or small errors



Event shapes



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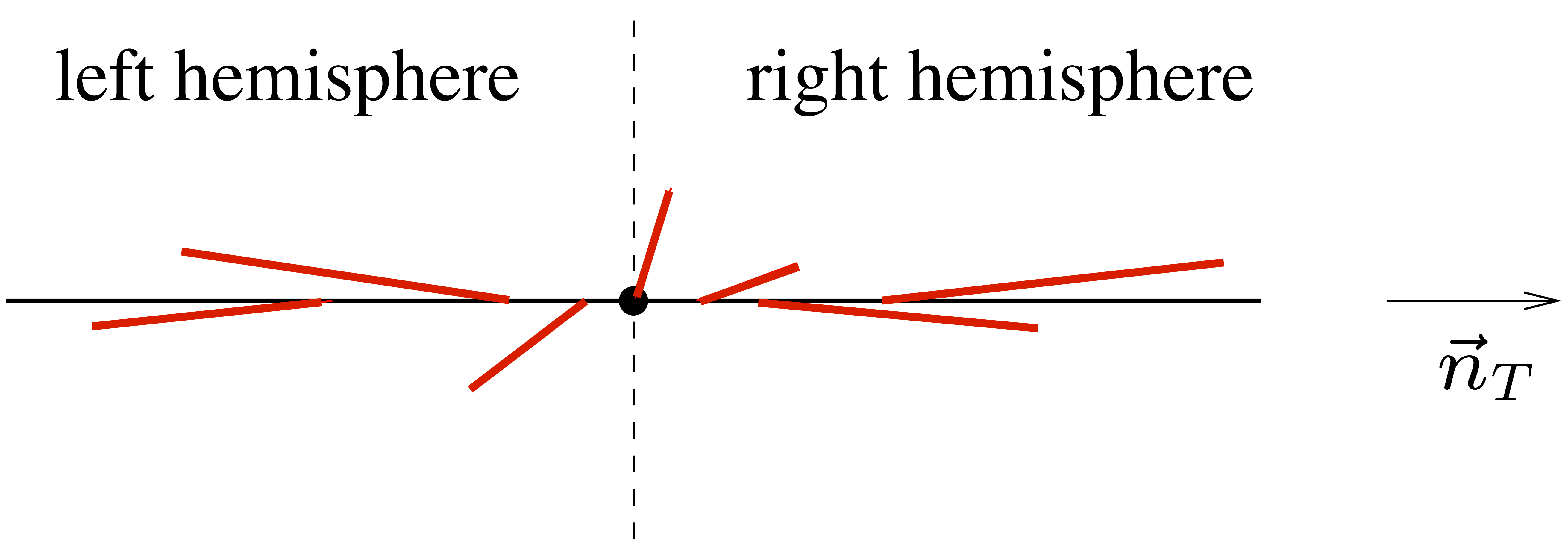


event shapes measure amount of radiation relative to simple $e^+e^- \to q\bar{q}$ event

thrust $\quad T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i.\vec{n}|}{\sum_i |\vec{p}_i|}\,, \qquad \tau = 1 - T\,,$

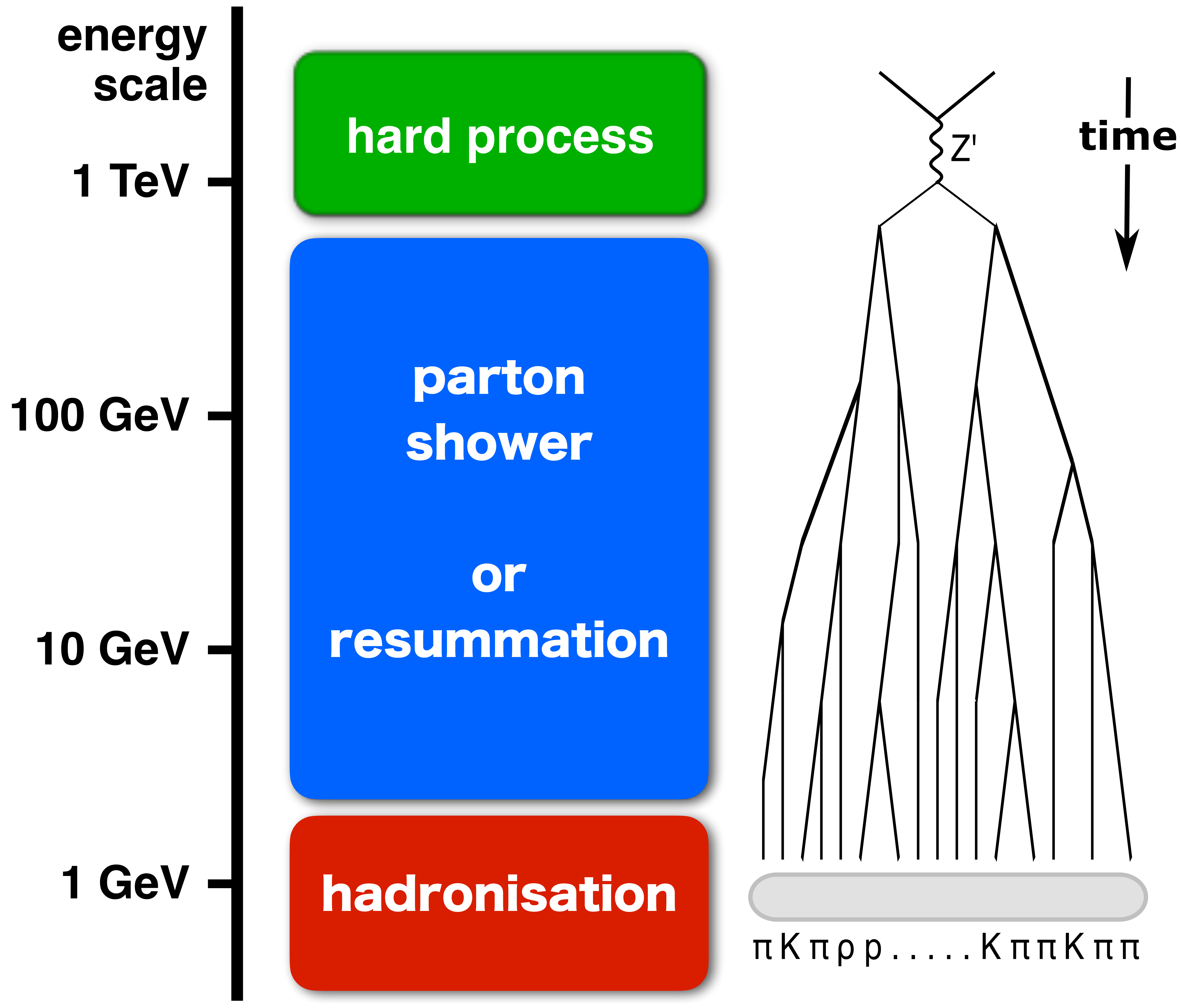
C-parameter $\quad C = \frac{3}{2}\frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{\left(\sum_i |\vec{p}_i|\right)^2}\,,$

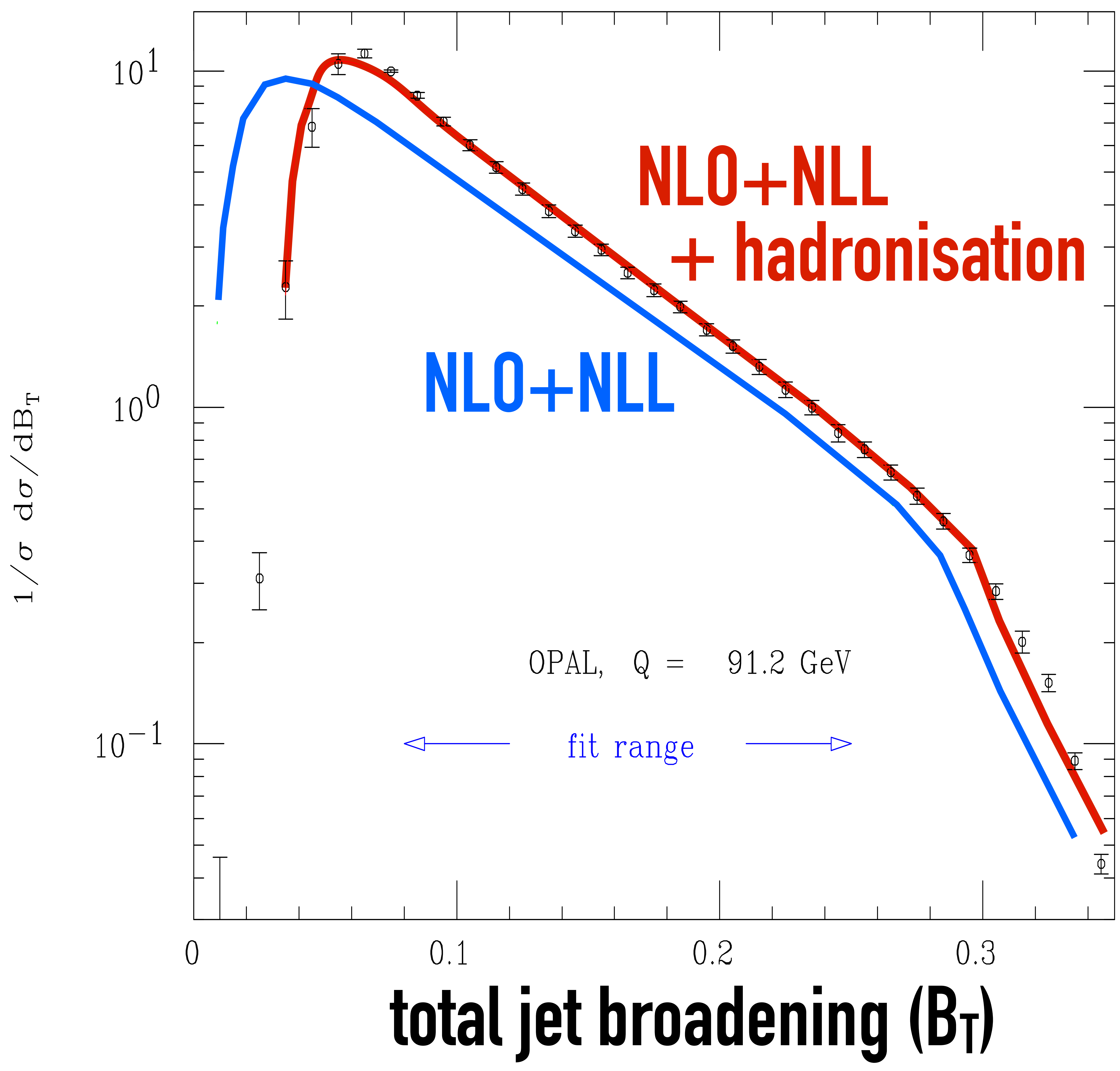
jet-mass $\quad \rho = \frac{\left(\sum_{i\in\text{hemisphere}} p_i\right)^2}{\left(\sum_i E_i\right)^2}\,,$

broadening $\quad B_T = \frac{\sum_i p_{ti}}{\sum_i |\vec{p}_i|}\,.$

NB: any issue that is present for event shapes is likely to be present also for pp & DIS jet measurements

non-perturbative physics & hadronisation: the bane of quantitative hadronic QCD





The standard approach

- Measure data at hadron ("particle") level
- Run a general purpose Monte Carlo
- Determine the observable at parton level
- Determine the observable at hadron level
- Use the difference to correct a perturbative parton-level calculation to hadron-level, for comparison to data

Fundamental & conceptual problem:
parton-level in a Monte Carlo ≠ parton-level in a perturbative calculation

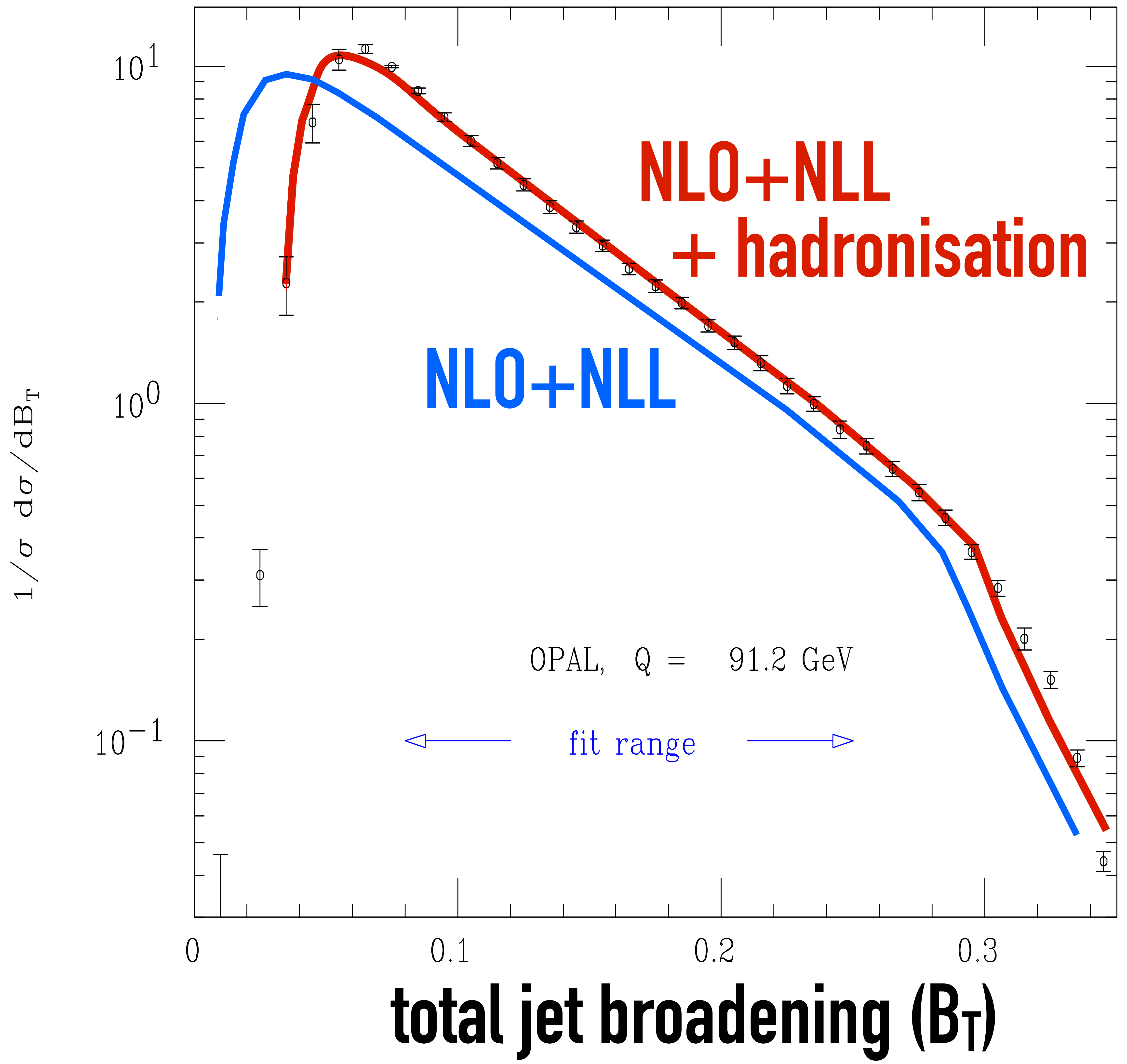
non-perturbative physics & hadronisation: the bane of quantitative collider QCD

c. 1995, theorists proposed analytical approaches to quantifying hadronisation (Dokshitzer, Marchesini & Webber; Beneke & Braun; Manohar & Wise; Korchemsky & Sterman).

$$\delta V \sim \frac{c_V \alpha_0}{Q}$$

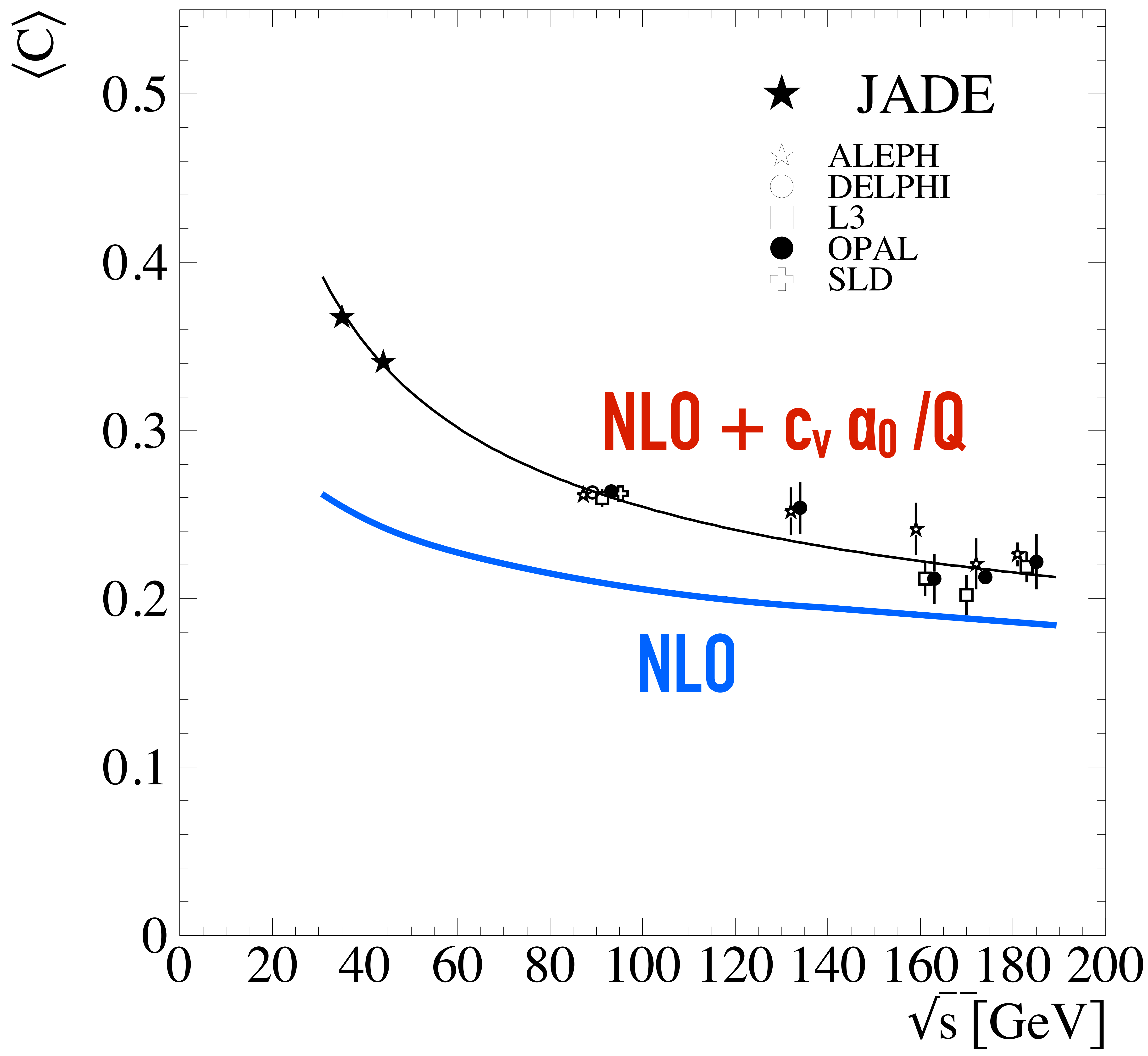
Did they match data?
Two key features to check:

- ➤ universality of α_0 across many shapes
- ➤ scaling with centre-of-mass energy Q



[JADE Collab, hep-ex/9903009](hep-ex/9903009)

Studies of average values of event shapes v. Q (CoM energy) gave support to analytical approaches that tried to work around this problem

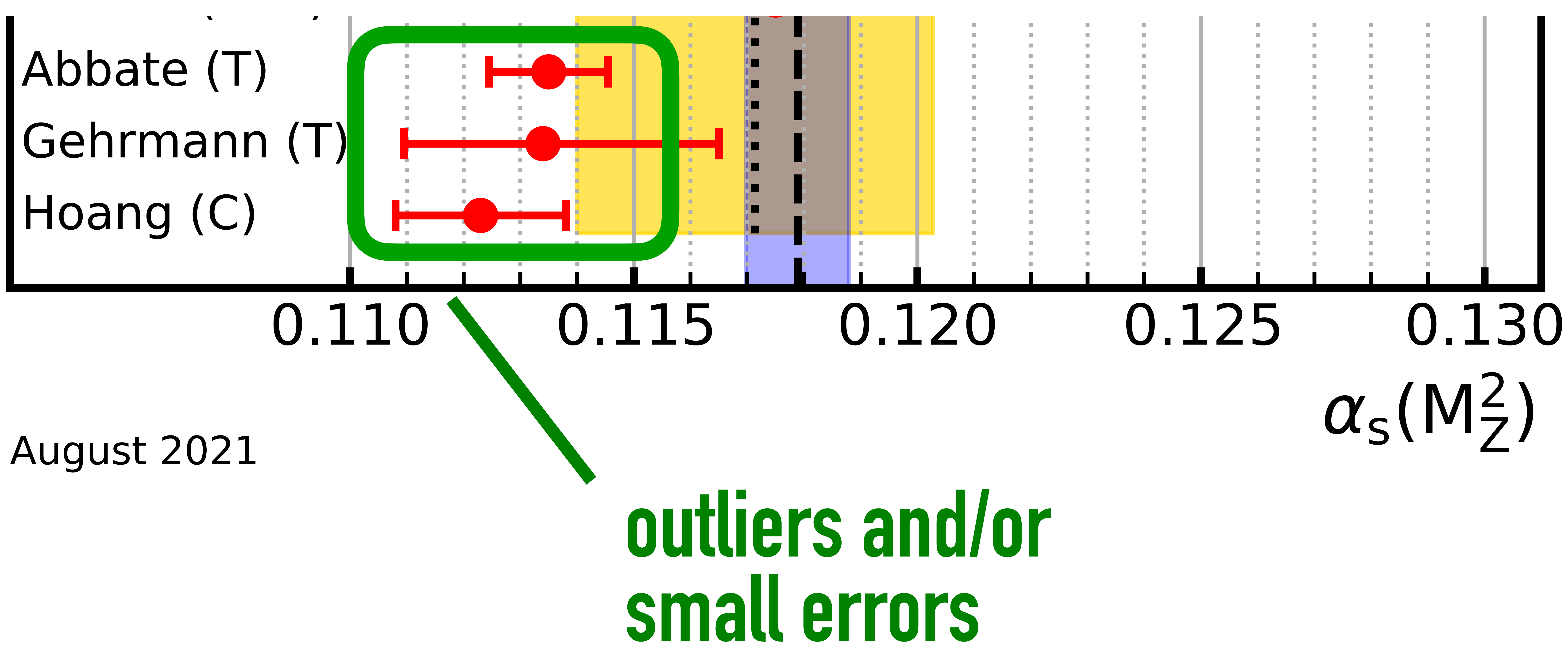


World average: $\alpha_s(m_Z) = 0.1179 \pm 0.0009$

Thrust: $\alpha_s(m_Z) = 0.1135 \pm 0.0002_{exp} \pm 0.0005_{hadr} \pm 0.0009_{pert}$ 1006.3080

C-parameter: $\alpha_s(m_Z) = 0.1119 \pm 0.0006_{exp+had} \pm 0.0013_{pert}$ 1501.04111

NNLO + N3LL **+ 1/*Q***



non-perturbative shift as f^n of C

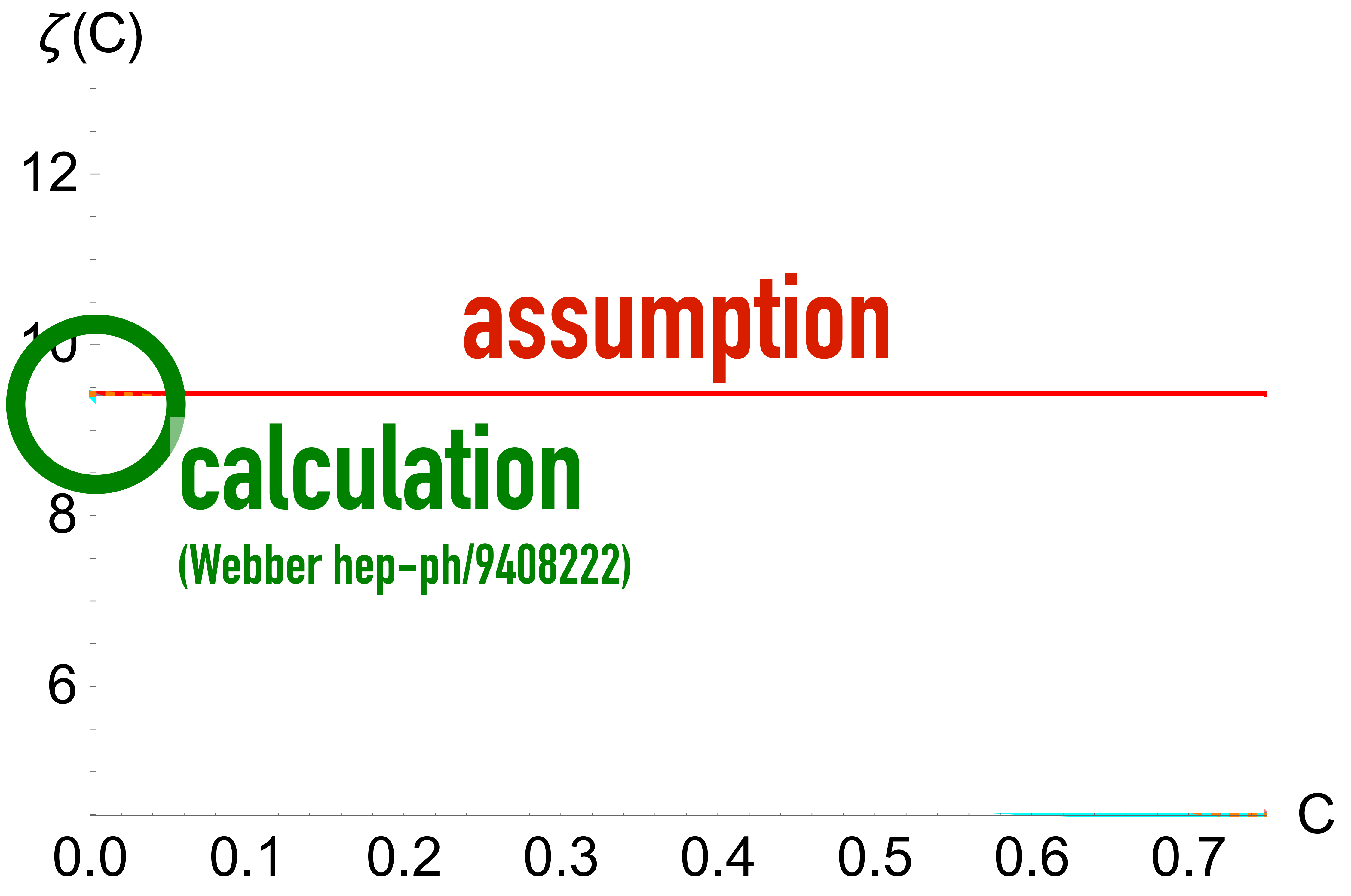


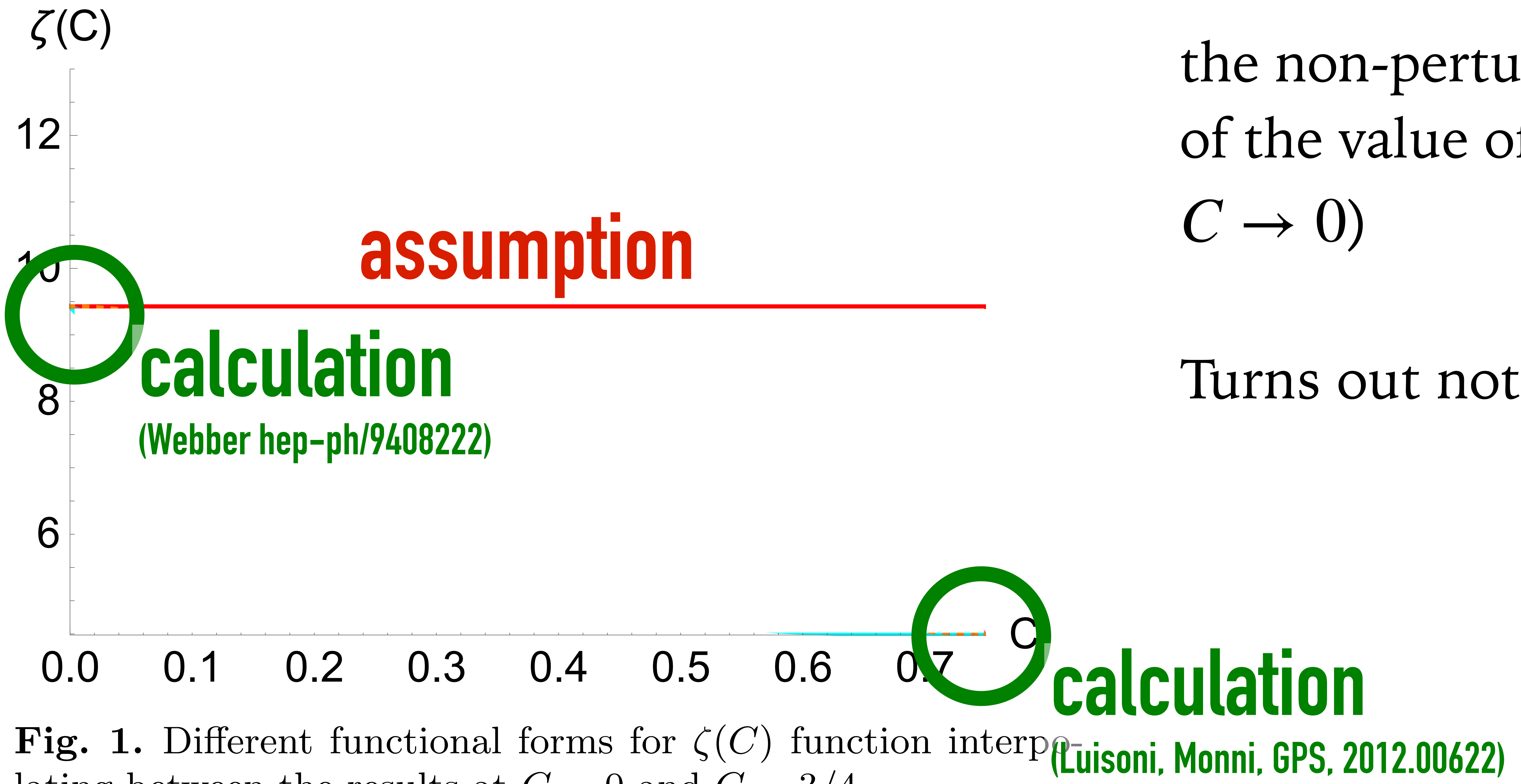
Fig. 1. Different functional forms for $\zeta(C)$ function interpolating between the results at $C = 0$ and $C = 3/4$.

critical assumption in those high-precision fits:

the non-perturbative shift is independent of the value of the observable (valid when $C \to 0$)

Turns out not be true

non-perturbative shift as f^n of C



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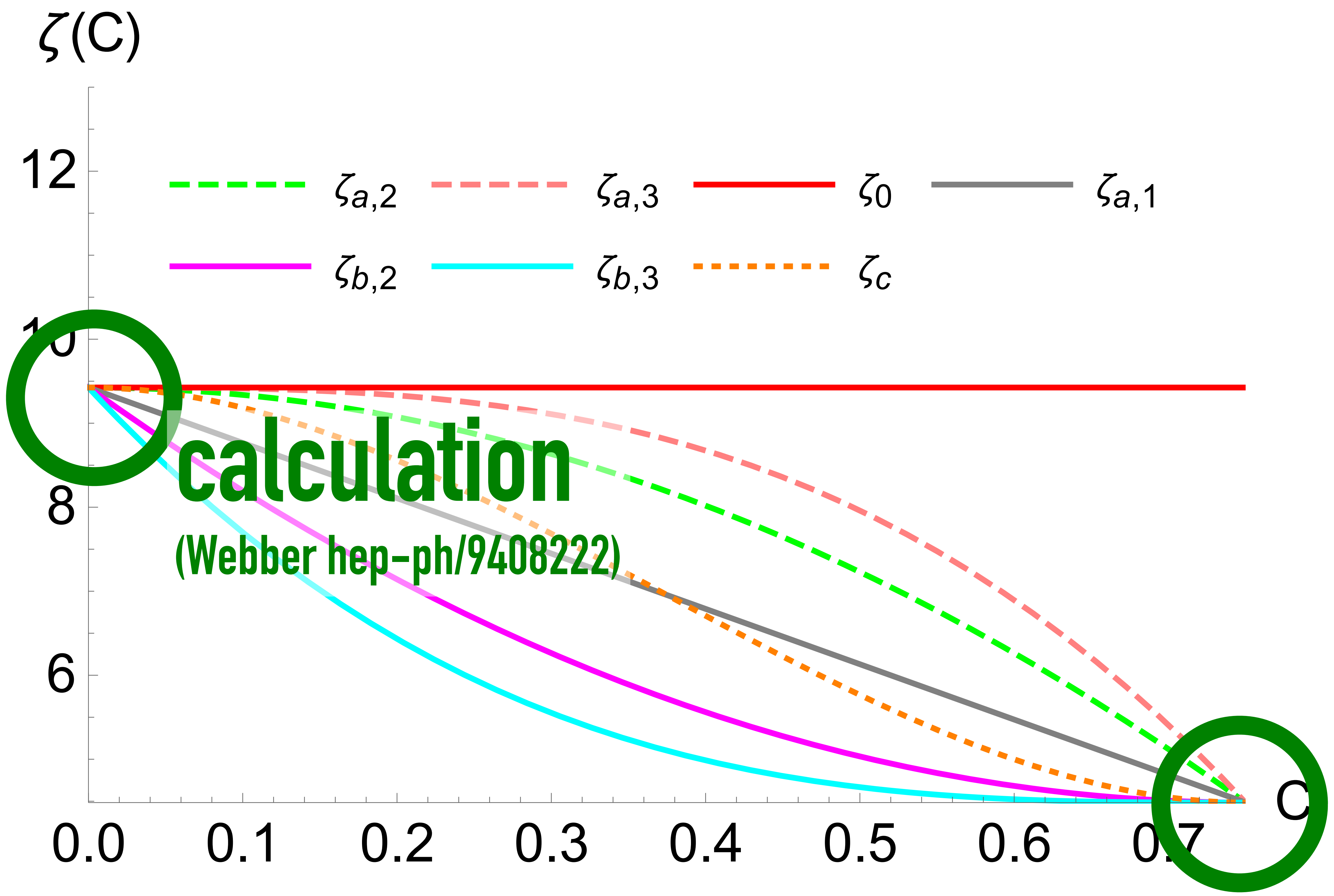
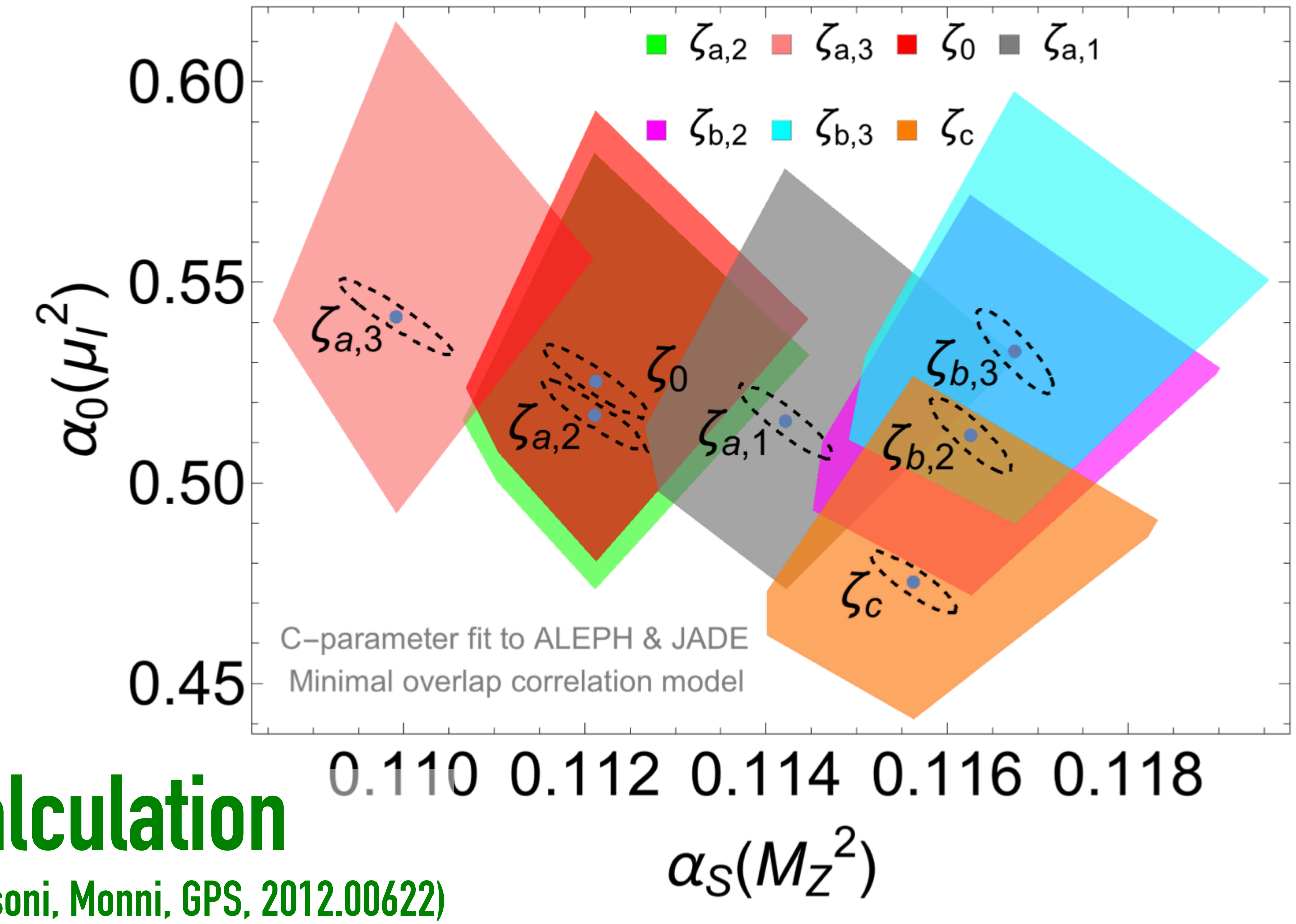


Fig. 1. Different functional forms for $\zeta(C)$ function interpolating between the results at $C = 0$ and $C = 3/4$.

calculation
(Luisoni, Monni, GPS, 2012.00622)

fit results with different interpolations



non-perturbative shift as f^n of C

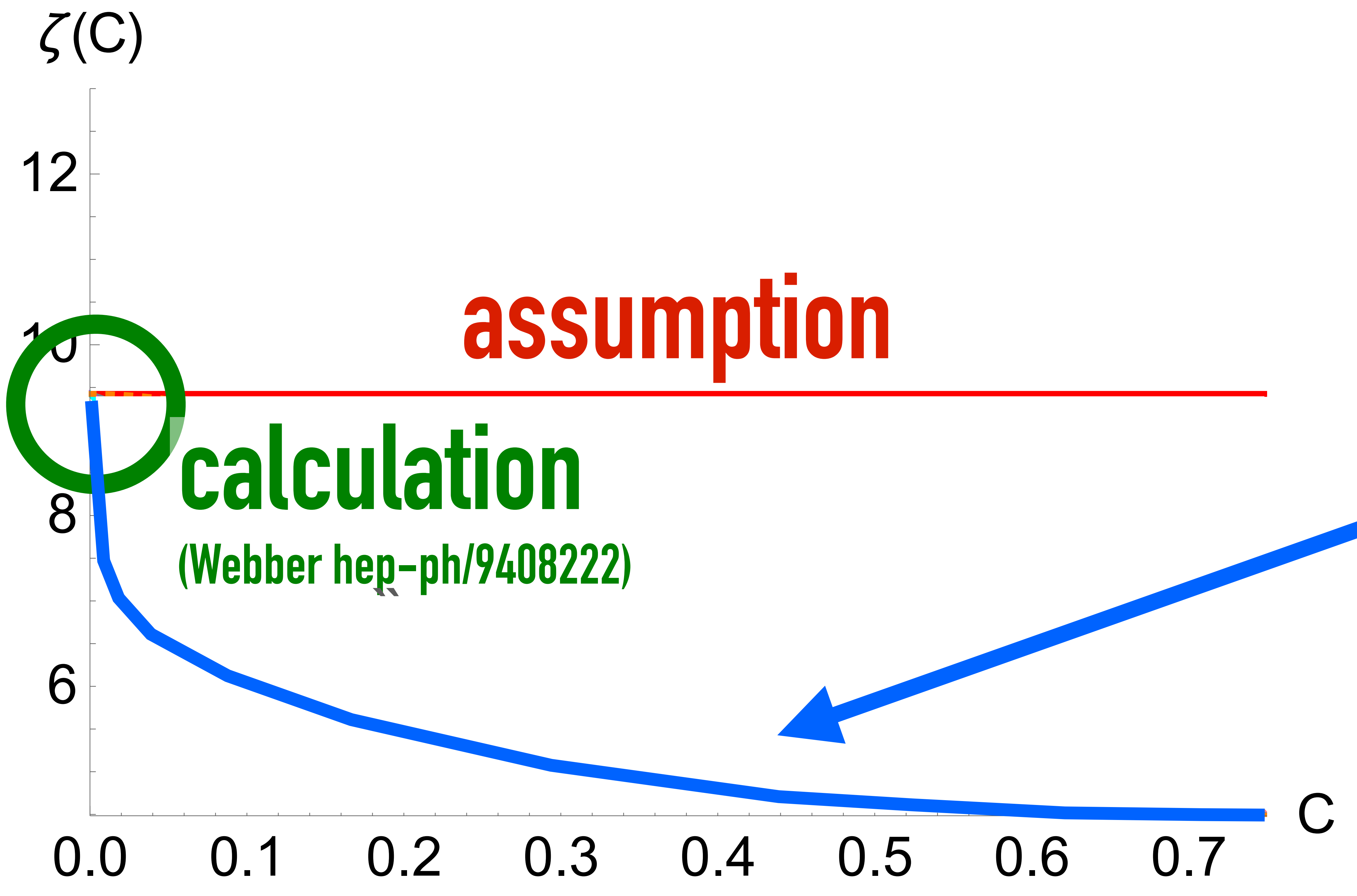
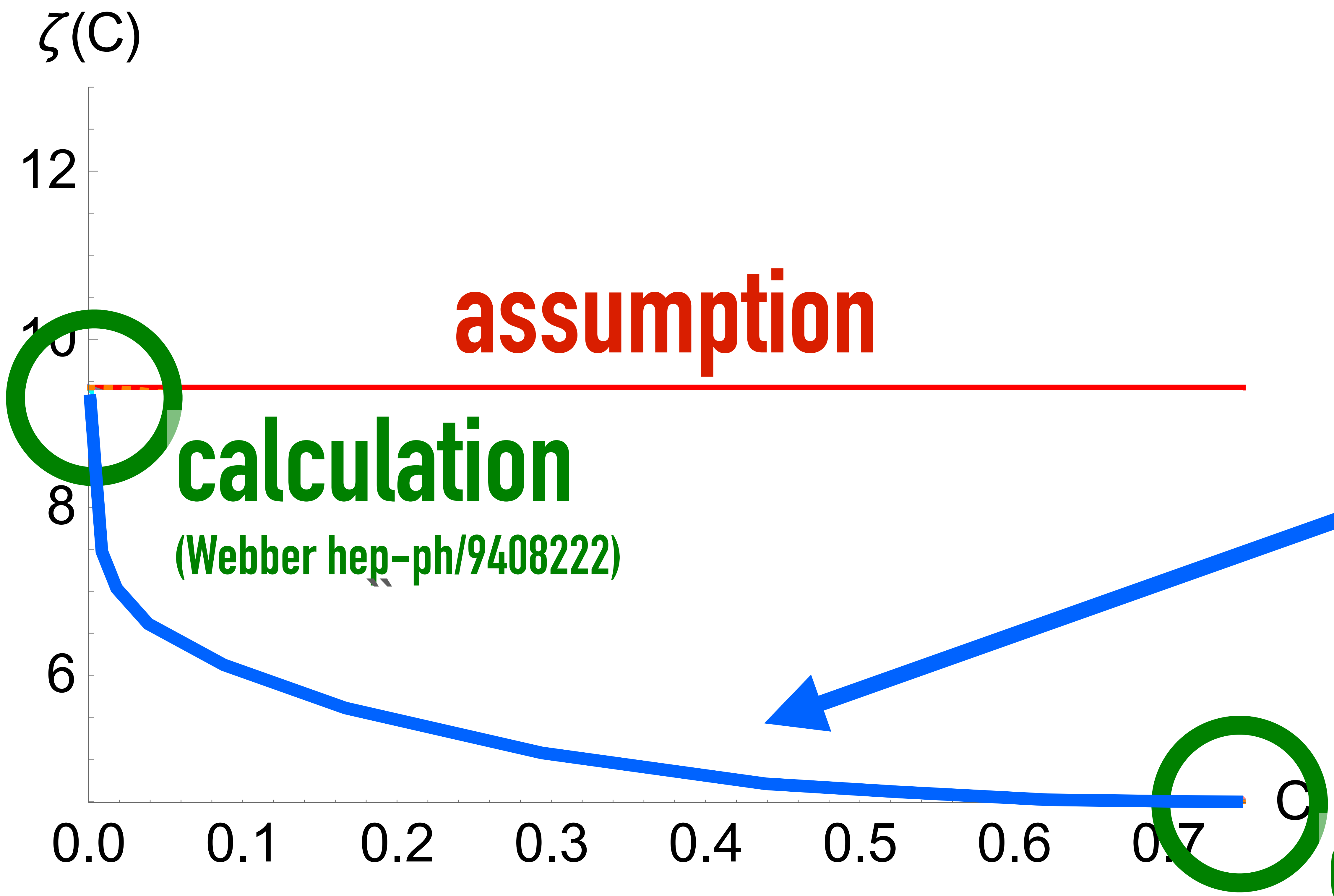


Fig. 1. Different functional forms for $\zeta(C)$ function interpolating between the results at $C = 0$ and $C = 3/4$.

full calculation

Caola, Ferrario Ravasio, Limatola, Melnikov, Nason, Ozcelik, 2204.02247

non-perturbative shift as f^n of C



full calculation

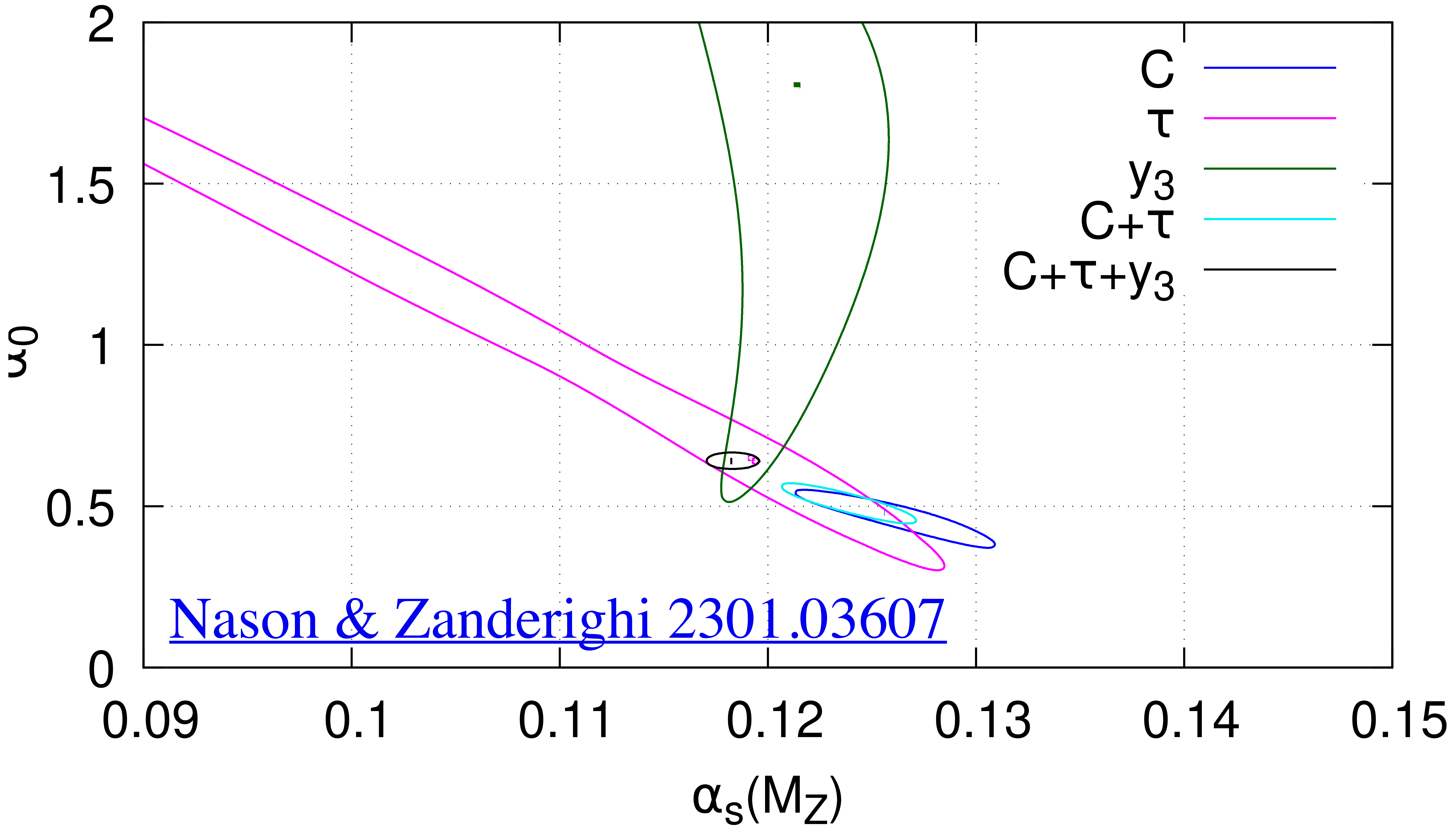
Caola, Ferrario Ravasio, Limatola, Melnikov, Nason, Ozcelik, 2204.02247

calculation

(Luisoni, Monni, GPS, 2012.00622)

Fig. 1. Different functional forms for $\zeta(C)$ function interpolating between the results at $C = 0$ and $C = 3/4$.

Fits with full (1st-order) non-perturbative correction



fits restricted to 3-jet region, NNLO + 1/Q

fixed 1/Q: $\alpha_s = 0.1132$

full 1/Q: $\alpha_s = 0.1182$

"variations of our procedure can lead easily to differences of the order of a percent"

confirms strong sensitivity to our understanding of non-perturbative physics

the non-perturbative part at hadron colliders

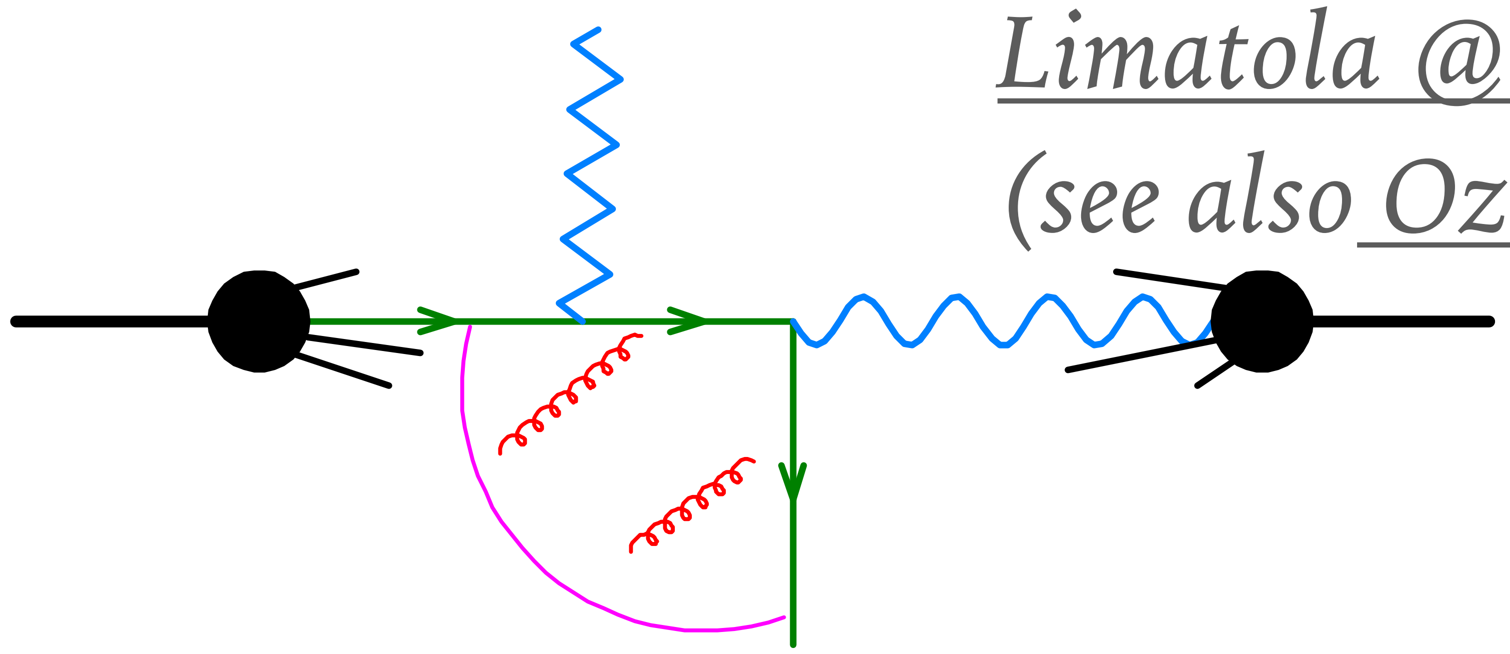
$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

What is value of p in $(\Lambda/Q)^p$? [Λ ~ 1 GeV]

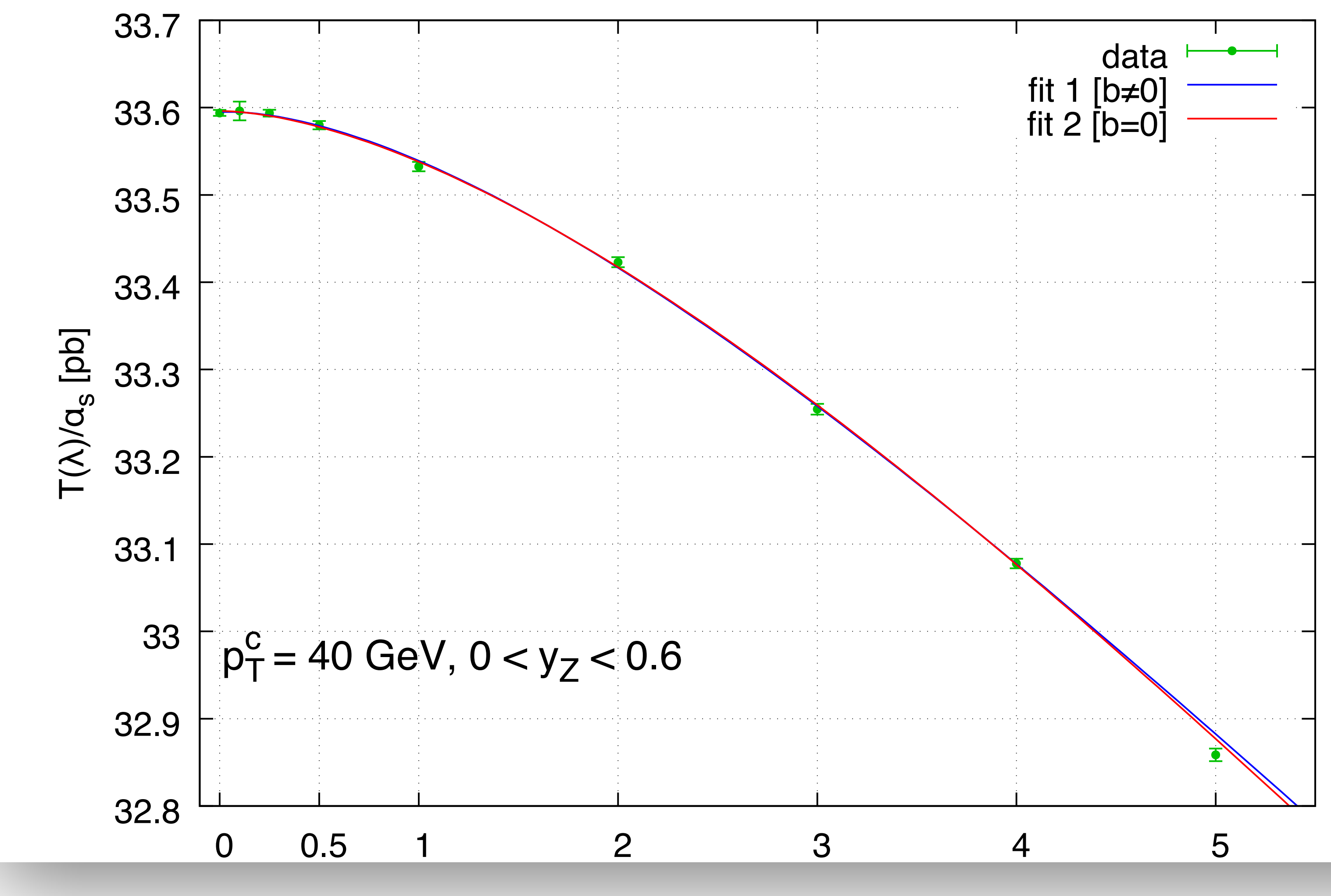
- Jet physics at LHC is dirty because $p = 1$ (hadronisation & MPI)
- LEP event-shape (C-parameter, thrust) α_s fit troubles are complex about because $p = 1$, $\Lambda \sim 0.5\,\text{GeV} \rightarrow (\Lambda/20\text{GeV}) \sim 2.5\,\%$
- Hadron-collider inclusive and rapidity-differential Drell-Yan cross sections are believed to have $p = 2$ (Higgs hopefully also), so leptonic / photonic decays should be clean, aside from isolation.
  $\Lambda \sim 0.5\,\text{GeV} \rightarrow (\Lambda/125\text{GeV})^2 \sim 0.002\,\%$
  [Beneke & Braun, hep-ph/9506452; Dasgupta, hep-ph/9911391]
- But at LHC, we're also interested in Z, W and Higgs production with non-zero p_T
  Nobody knew if we have $(\Lambda/p_T)^p$ with $p = 1$ (a disaster) or $p = 2$ (all is fine)

What is value of p in $(\Lambda/Q)^p$ for Z p_T?

- We consider the process $d(p_1)\gamma(p_2) \to Z(p_3)d(p_4)$ to work in the *Large-n_f* limit and to preserve the azimuthal color asymmetry ($E_{CM} = 300$ GeV)



Limatola @ ICHEP'22
(see also Ozcelik @ ICHEP)



We (Ferrario Ravasio, GL, Nason ('20)) found

$$\langle O\rangle_\lambda^{(1)} \sim \left(\frac{\lambda}{p_T^c}\right)^2 \log\left(\frac{\lambda}{p_T^c}\right)$$

No numeric evidence of a IR linear renormalon for the transverse momentum of the Z boson!

absence of p=1 term critical for viability of LHC precision programme

But note the log factor in p=2 term — is this captured in intrinsic-p_T models?

Ferraro Ravasio, Limatola & Nason, 2011.14114

+ analytic demonstration in Caola, Ferrario Ravasio, Limatola, Melnikov & Nason, 2108.08897 , idem + Ozcelik 2204.02247

What is value of p in $(\Lambda/Q)^p$ for top production?

Linear power corrections to top quark pair production in hadron collisions #1

Sergei Makarov (Karlsruhe U., TTP), Kirill Melnikov (Karlsruhe U., TTP), Paolo Nason (INFN, Milan Bicocca), Melih A. Ozcelik (IJCLab, Orsay) (Aug 10, 2023)

e-Print: 2308.05526 [hep-ph]

pdf cite claim reference search 0 citations

Linear power corrections to single top production processes at the LHC #2

Sergei Makarov (Karlsruhe U., TTP), Kirill Melnikov (Karlsruhe U., TTP), Paolo Nason (INFN, Milan Bicocca and Munich, Max Planck Inst.), Melih A. Ozcelik (Karlsruhe U., TTP and IJCLab, Orsay) (Feb 6, 2023)

Published in: *JHEP* 05 (2023) 153 • e-Print: 2302.02729 [hep-ph]

pdf DOI cite claim reference search 1 citation

All-orders behaviour and renormalons in top-mass observables #5

Silvia Ferrario Ravasio (Milan Bicocca U. and INFN, Milan Bicocca), Paolo Nason (CERN and INFN, Milan Bicocca), Carlo Oleari (INFN, Milan Bicocca and Milan Bicocca U.) (Oct 25, 2018)

Published in: *JHEP* 01 (2019) 203 • e-Print: 1810.10931 [hep-ph]

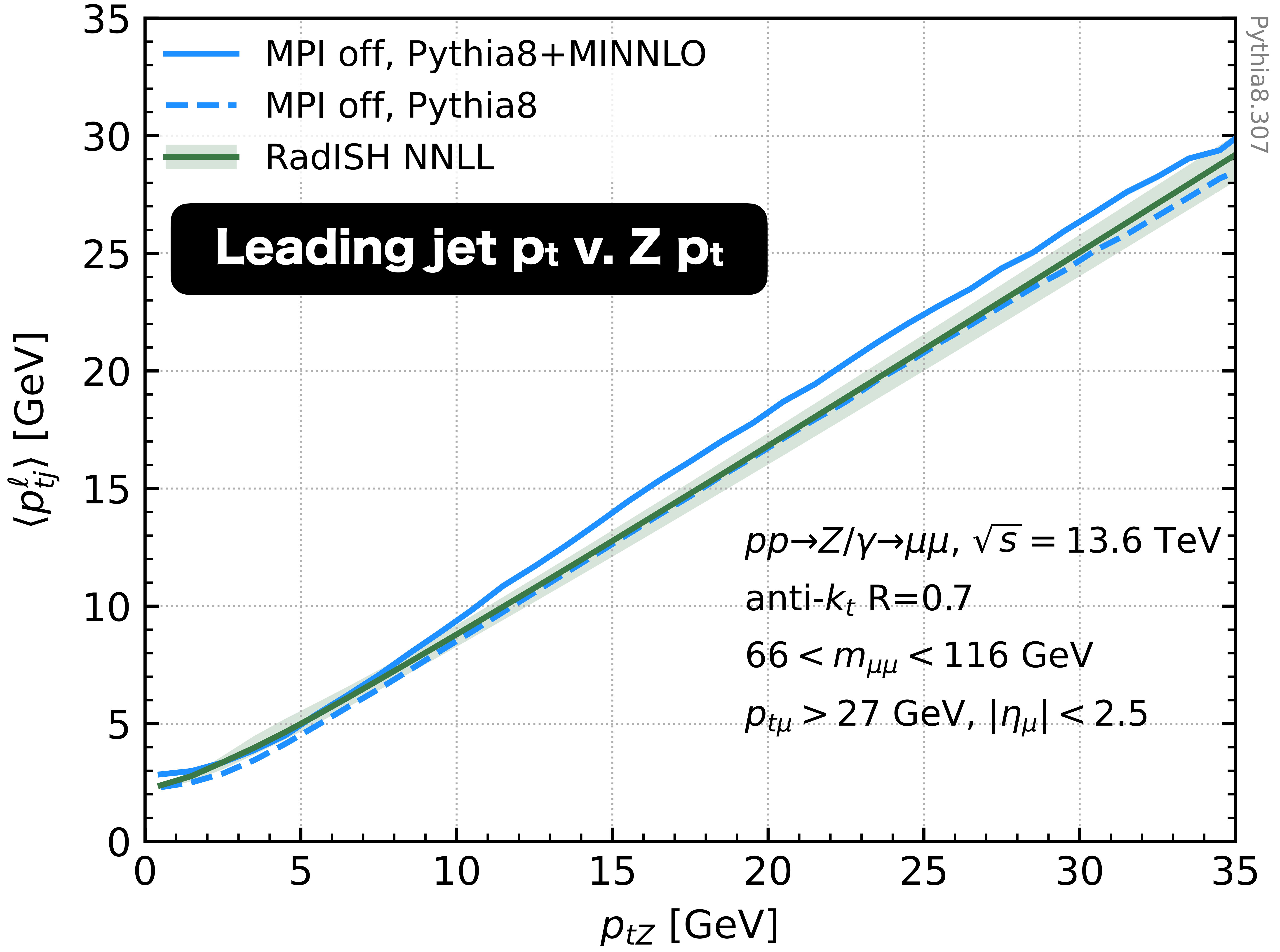
pdf DOI cite claim reference search 30 citations

unless you choose a very special observable

p=1

Underlying event & jets: $\Lambda/Q \to$ (several GeV)/Q

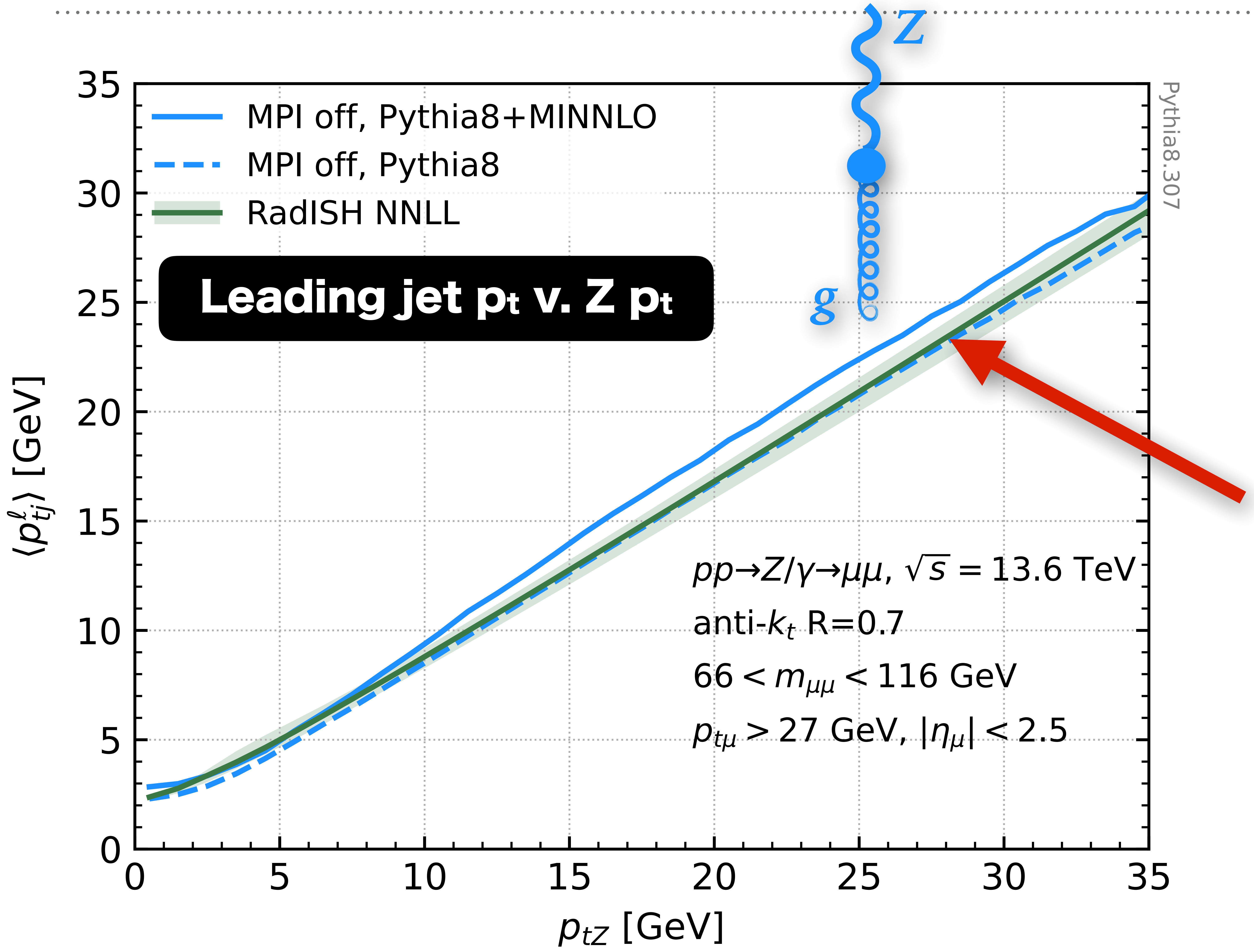
Andersen, Monni, Rottoli, GPS & Soto Ontoso, 2307.05693



- Consider process with **MPI simulation turned off** (i.e. just 1HS)
- Look at avg. p_t of leading jet (p_{tj}^{ℓ}) as a function of Z p_t (p_{tZ})

Underlying event & jets: Λ/Q → (several GeV)/Q

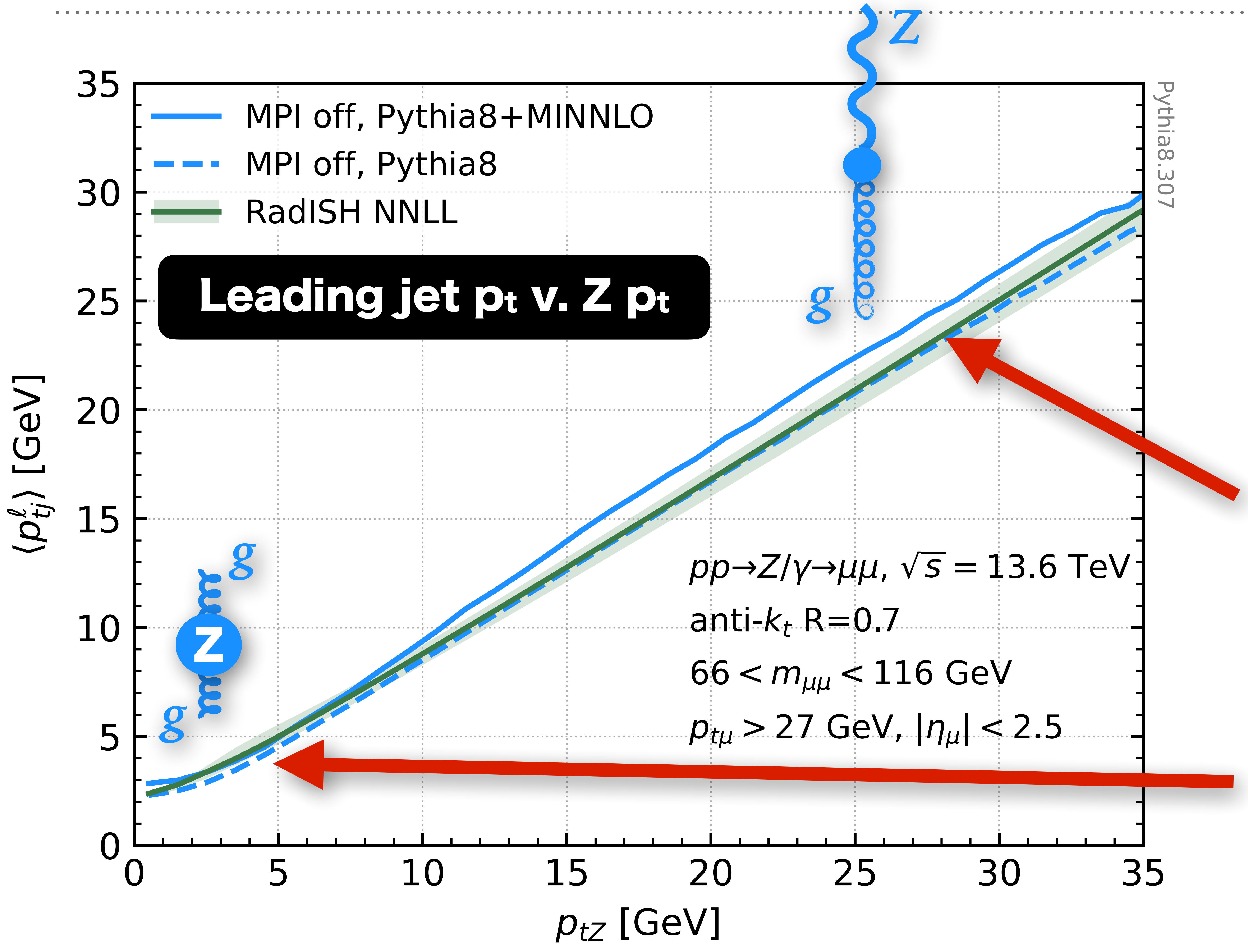
Andersen, Monni, Rottoli, GPS & Soto Ontoso, 2307.05693



- Consider process with **MPI simulation turned off** (i.e. just 1HS)
- Look at avg. p_t of leading jet (p_{tj}^{ℓ}) as a function of Z p_t (p_{tZ})
- **Most of p_{tZ} range:** almost perfect linear correlation, since **leading jet balances p_{tZ}**

Underlying event & jets: Λ/Q → (several GeV)/Q

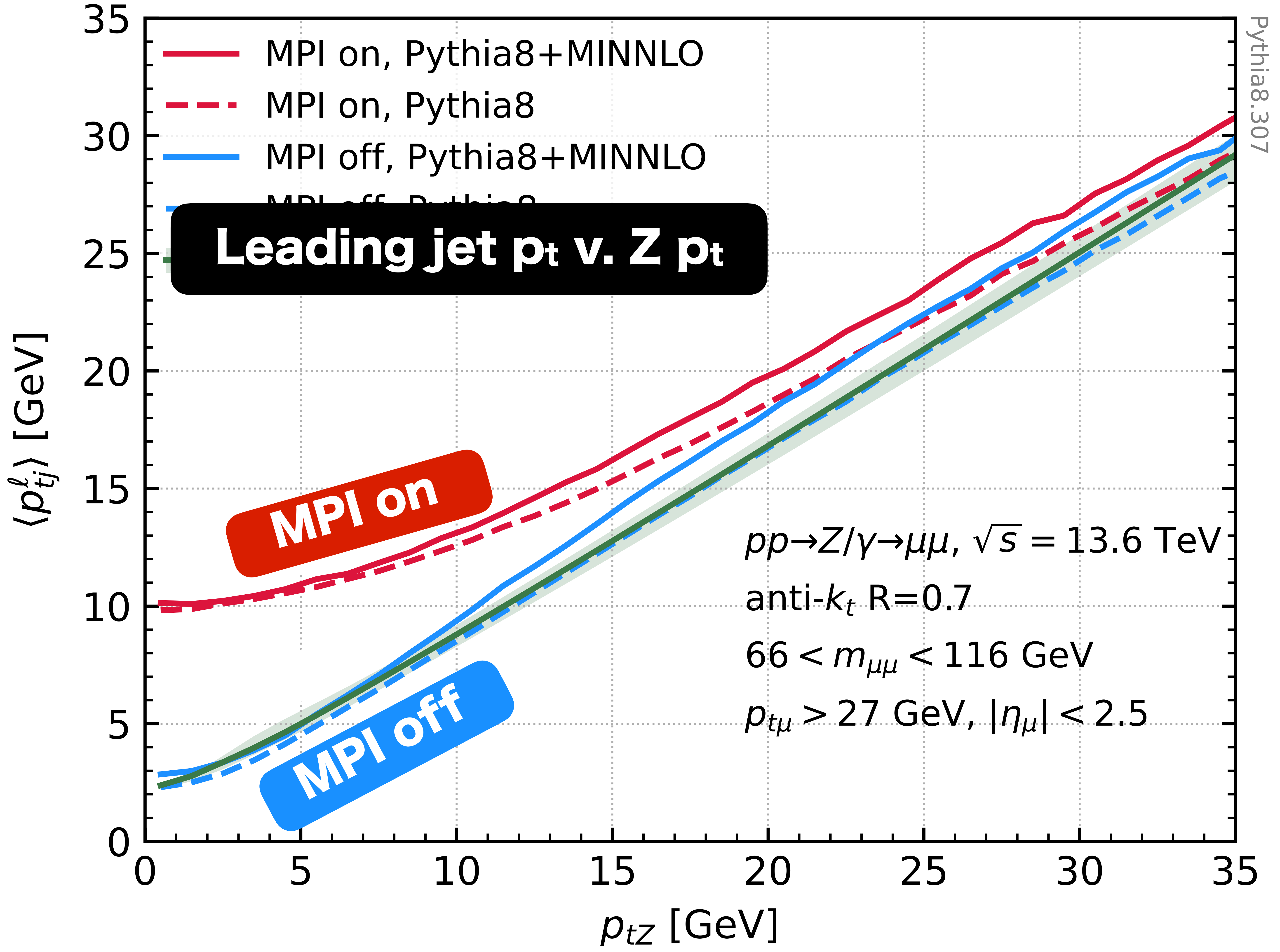
Andersen, Monni, Rottoli, GPS & Soto Ontoso, 2307.05693



- Consider process with **MPI simulation turned off** (i.e. just 1HS)
- Look at avg. p_t of leading jet (p_{tj}^{ℓ}) as a function of Z p_t (p_{tZ})
- **Most of p_{tZ} range:** almost perfect linear correlation, since **leading jet balances p_{tZ}**
- **For $p_{tZ} \to 0$:** $\langle p_{tj}^{\ell} \rangle$ saturates at about 2–3 GeV: **two soft jets balance each other**

Underlying event & jets: Λ/Q → (several GeV)/Q

Andersen, Monni, Rottoli, GPS & Soto Ontoso, 2307.05693



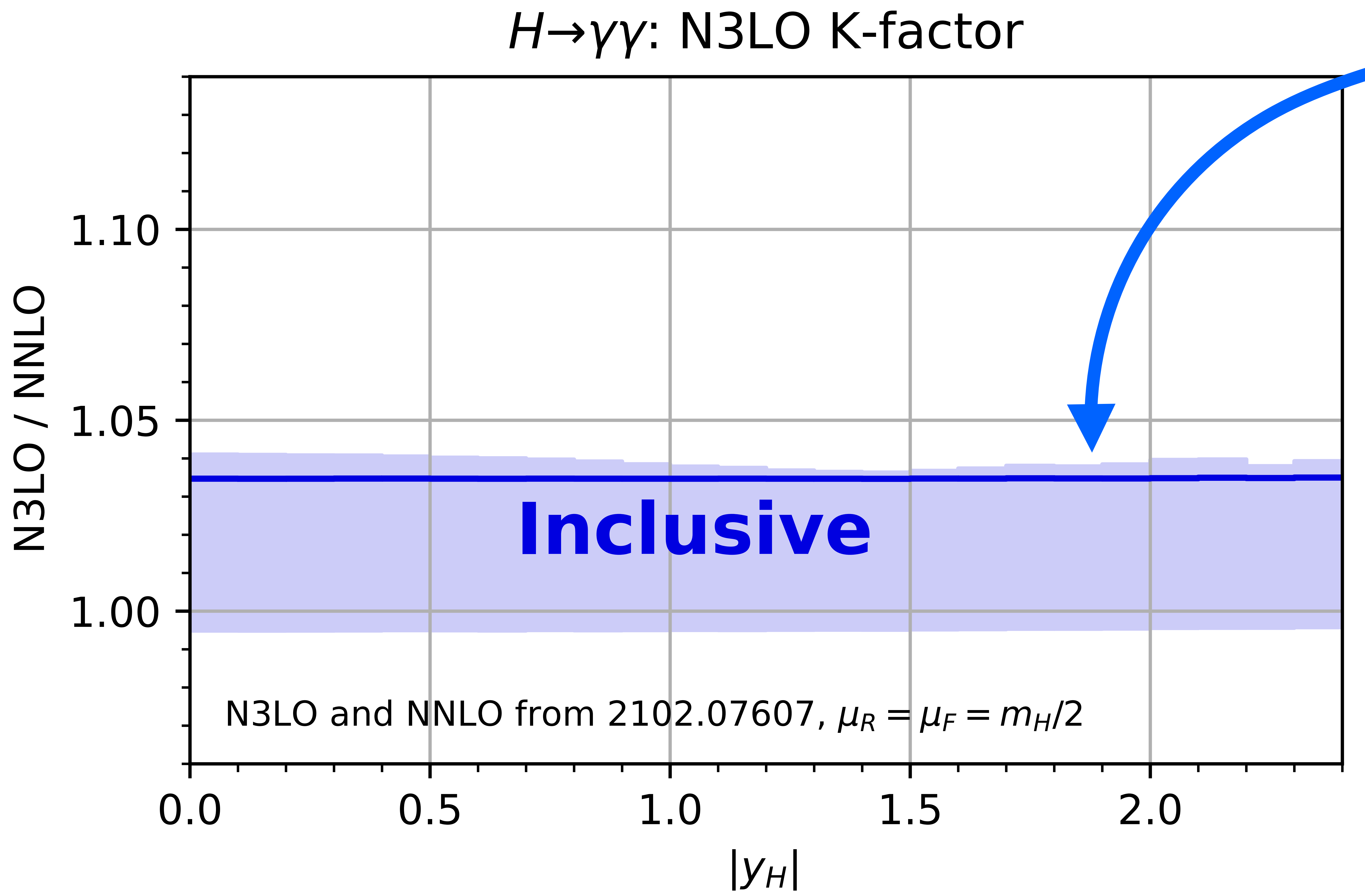
- next step: turn MPI on
- for $p_{tZ} \to 0$, leading jet p_t is now ∼10 GeV instead of 2–3 GeV [not so soft!]
- because there is almost always an MPI jet that is much harder than the soft jets from Z-process
- NB: jet studies take small radius of R=0.4, partly to mitigate MPI effects

spurious perturbative behaviour

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

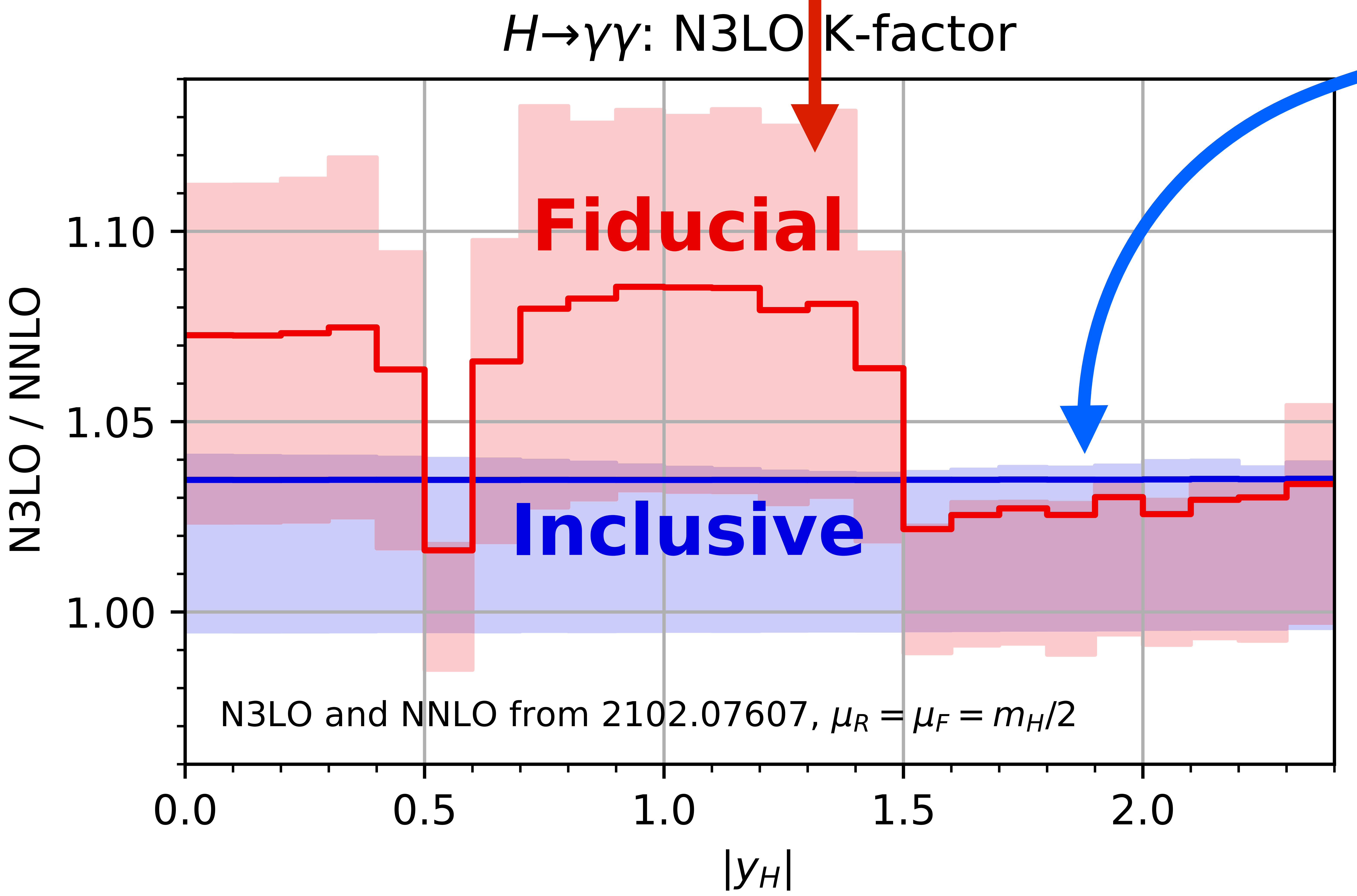
Recent surprise: H→γγ

inclusive N3LO σ uncertaities



Chen, Gehrmann, Glover, Huss, Mistlberger & Pelloni, 2102.07607

Recent surprise: H→γγ fiducial N3LO σ uncertainties ~2× greater than inclusive N3LO σ uncertaities

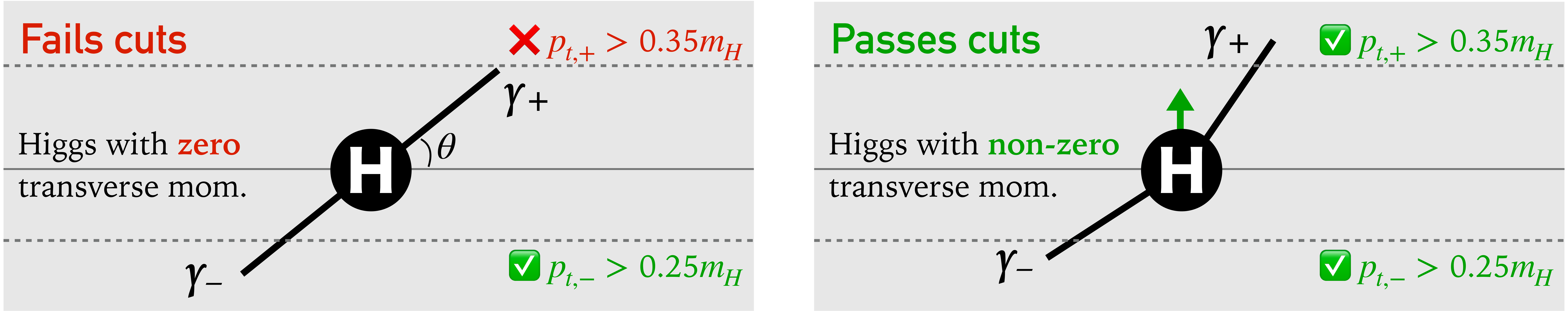


“Gold standard” fiducial cross section gives much worse prediction

Why?
And can this be solved?

Chen, Gehrmann, Glover, Huss, Mistlberger & Pelloni, 2102.07607

Standard $p_{t,\gamma}$ cuts → Higgs p_t dependence of acceptance

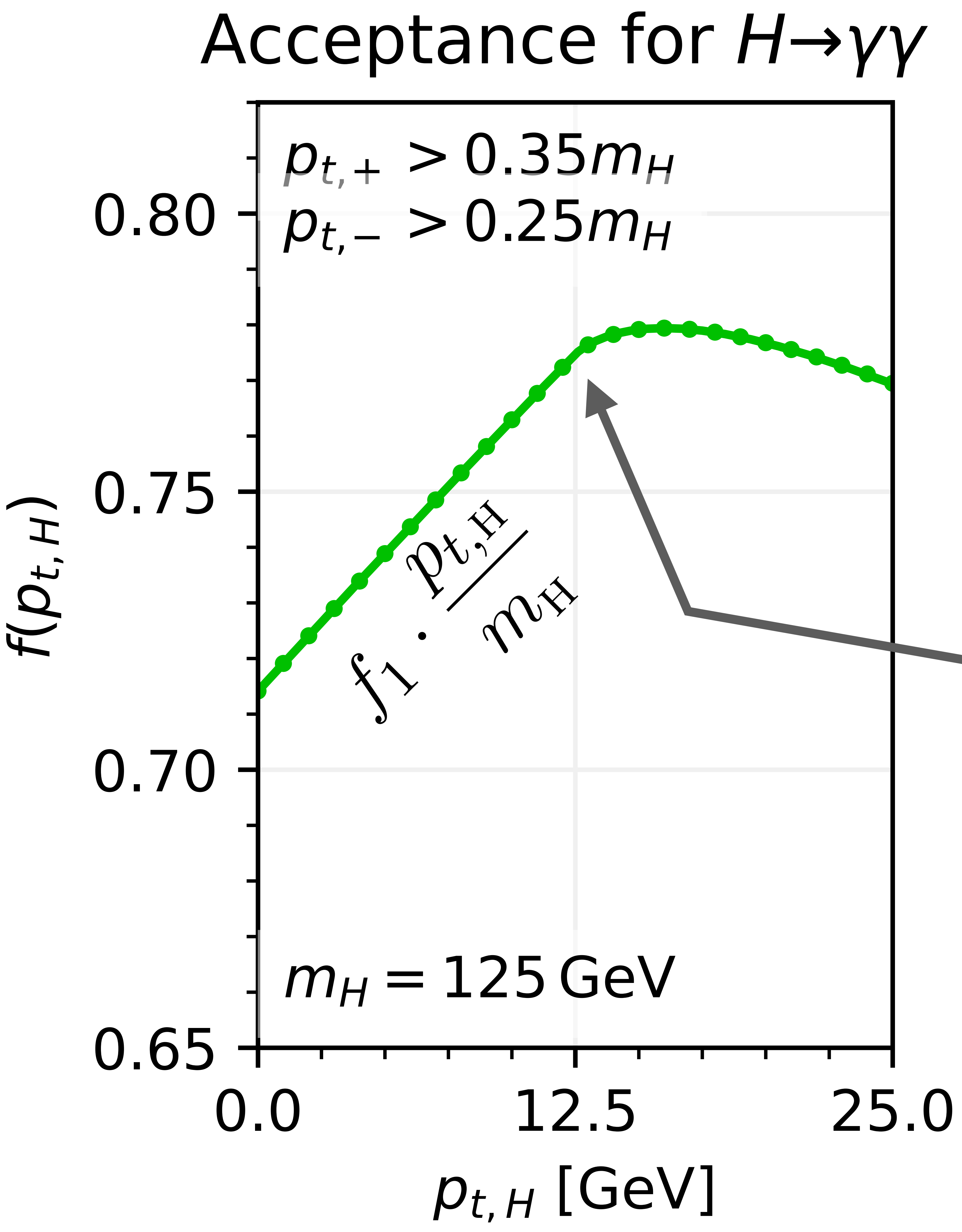


Numbers are for ATLAS H→ γγ p_t cuts, CMS cuts are similar

Expect acceptance to **increase with increasing $p_{t,\mathrm{H}}$**

$$p_{t,\pm}(p_{t,\mathrm{H}}, \theta, \phi) = \frac{m_\mathrm{H}}{2} \sin\theta \pm \frac{1}{2} p_{t,\mathrm{H}} |\cos\phi| + \frac{p_{t,\mathrm{H}}^2}{4 m_\mathrm{H}} \left(\sin\theta \cos^2\phi + \csc\theta \sin^2\phi\right) + \mathcal{O}_3\,,$$

Linear p_{tH} dependence of H acceptance ≡ $f(p_{tH})$



$$f(p_{t,\mathrm{H}}) = f_0 + f_1 \cdot \frac{p_{t,\mathrm{H}}}{m_\mathrm{H}} + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_\mathrm{H}^2}\right)$$

See e.g. Frixione & Ridolfi '97
Ebert & Tackmann '19
idem + Michel & Stewart '20
Alekhin et al '20

f_0 and f_1 are coefficients whose values depend on the cuts

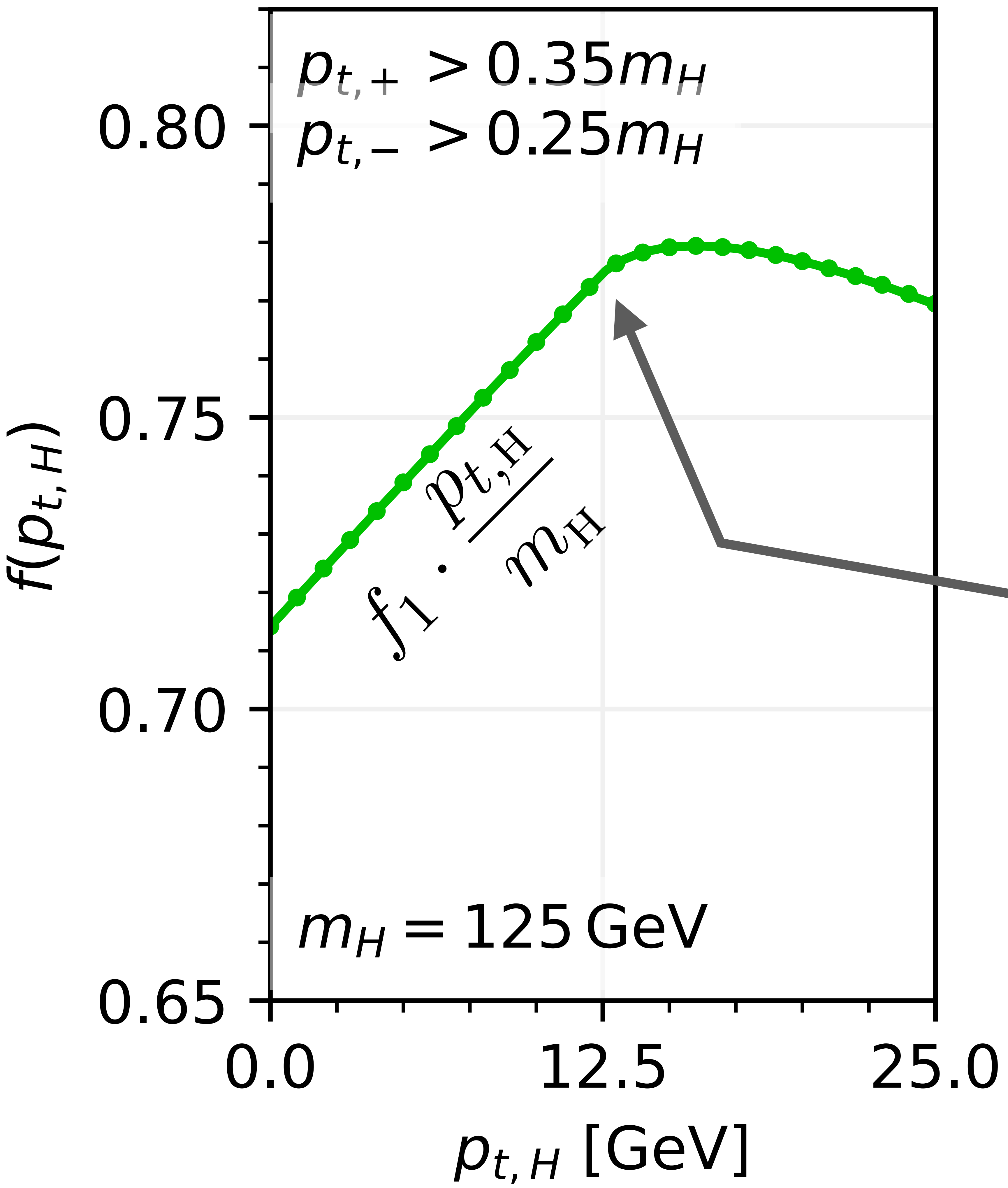
effect of $p_{t,-}$ cut sets in at $0.1 m_\mathrm{H}$

define $s_0 = \frac{2 p_{t+,\mathrm{cut}}}{m_H}$: $f_0 = \sqrt{1 - s_0^2} \simeq 0.71, f_1 = \frac{2 s_0}{\pi f_0} \simeq 0.62$

transition is at $p_{t+,cut} - p_{t-,cut}$

Linear p_{tH} dependence of H acceptance ≡ $f(p_{tH})$

Acceptance for $H \to \gamma\gamma$



$$f(p_{t,\mathrm{H}}) = f_0 + f_1 \cdot \frac{p_{t,\mathrm{H}}}{m_\mathrm{H}} + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_\mathrm{H}^2}\right)$$

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Alekhin et al '20

f_0 and f_1 are coefficients whose values depend on the cuts

effect of $p_{t,-}$ cut sets in at $0.1 m_\mathrm{H}$

$p_{t,\mathrm{H}}$ dependence of acceptance (at 10% level) → relating measured cross section and total cross section requires info about the $p_{t,\mathrm{H}}$ distribution.

perturbative series for fiducial cross sections

$$f(p_{t,\mathrm{H}}) = f_0 + f_1 \cdot \frac{p_{t,\mathrm{H}}}{m_\mathrm{H}} + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_\mathrm{H}^2}\right)$$

Fiducial cross section depends on acceptance and Higgs p_t distribution

$$\sigma_\mathrm{fid} = \int \frac{d\sigma}{dp_{t,\mathrm{H}}} f(p_{t,\mathrm{H}}) dp_{t,\mathrm{H}}$$

To understand qualitative perturbative behaviour consider simple (double-log) approx for p_t distribution

$$\frac{d\sigma^\mathrm{DL}}{dp_{t,\mathrm{H}}} = \frac{\sigma_\mathrm{tot}}{p_{t,\mathrm{H}}} \sum_{n=1}^{\infty} (-1)^{n-1} \frac{2\log^{2n-1}\frac{m_\mathrm{H}}{2p_{t,\mathrm{H}}}}{(n-1)!} \left(\frac{2C_A\alpha_s}{\pi}\right)^n$$

$$\int_0^{m_H} \frac{dp_{t,H}}{p_{t,H}} \frac{\alpha_s^n}{(n-1)!} \left(\log \frac{m_H}{p_{t,H}}\right)^{2n-1} \cdot \left(\frac{p_{t,H}}{m_H}\right) \sim \alpha_s^n \frac{(2n-1)!}{(n-1)!} \sim \alpha_s^n\, 2^{2n} n!$$

GPS & Slade, 2106.08329

Behaviour of perturbative series in various log approximations

Resummed results

$$\frac{\sigma_{\text{asym}} - f_0\sigma_{\text{inc}}}{\sigma_0 f_0} \simeq 0.15_{\alpha_s} - 0.29_{\alpha_s^2} + 0.71_{\alpha_s^3} - 2.39_{\alpha_s^4} + 10.31_{\alpha_s^5} + \ldots \simeq 0.06 \quad \text{@DL},$$
$$\simeq 0.15_{\alpha_s} - 0.23_{\alpha_s^2} + 0.44_{\alpha_s^3} - 1.15_{\alpha_s^4} + 3.86_{\alpha_s^5} + \ldots \simeq 0.06 \quad \text{@LL},$$
$$\simeq 0.18_{\alpha_s} - 0.15_{\alpha_s^2} + 0.29_{\alpha_s^3} + \ldots \simeq 0.10 \quad \text{@NNLL},$$
$$\simeq 0.18_{\alpha_s} - 0.15_{\alpha_s^2} + 0.31_{\alpha_s^3} + \ldots \simeq 0.12 \quad \text{@N3LL}.$$

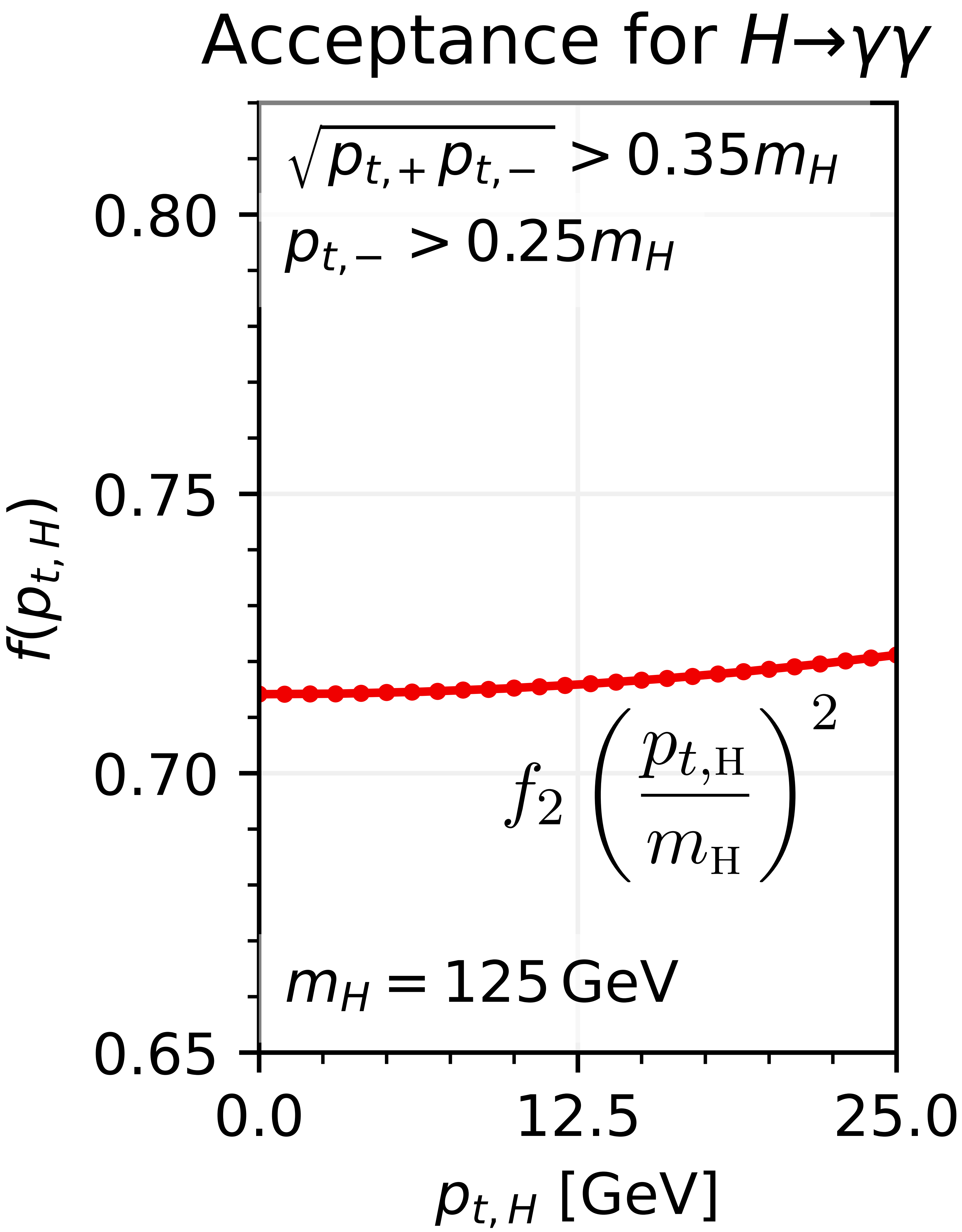
Thanks to Pier Monni & RadISH for supplying NN(N)LL distributions & expansions, $\mu = m_H/2$

(relative to previous slide, this now has full expression for acceptance)

- At DL & LL (DL+running coupling) **factorial divergence sets in from first orders**
- Poor behaviour of N3LL is qualitatively similar to that seen by Billis et al '21
- Theoretically similar to a power-suppressed ambiguity $\sim (\Lambda_{\text{QCD}}/m_{\text{H}})^{0.205}$ [inclusive cross sections expected to have Λ^2/m^2]

GPS & Slade, 2106.08329

Replace cut on leading photon → cut on **product of photon p_t's**

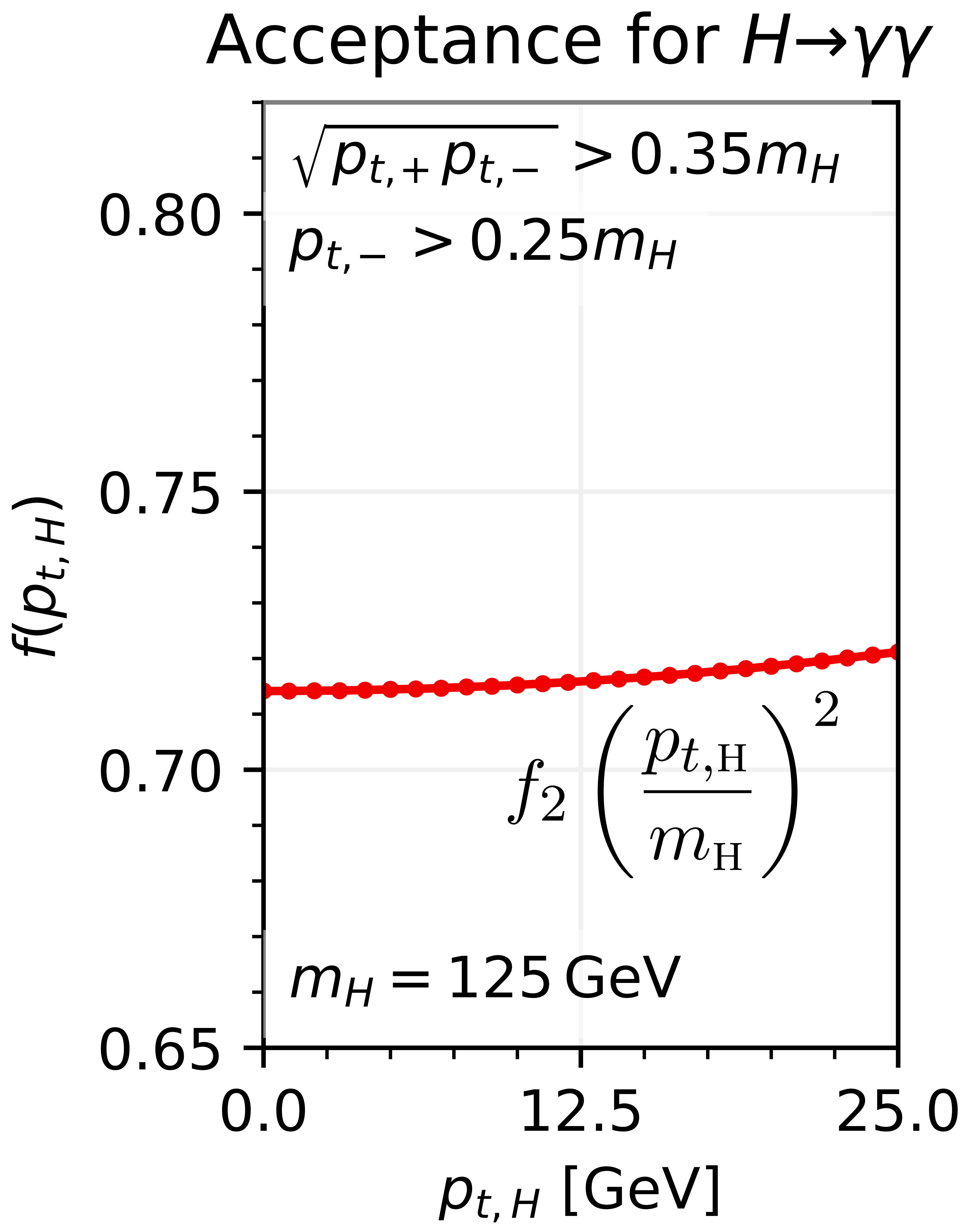


$$f(p_{t,\mathrm{H}}) = f_0 + f_2\left(\frac{p_{t,\mathrm{H}}}{m_\mathrm{H}}\right)^2 + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_\mathrm{H}^2}\right)$$

linear → quadratic

NB: the cut on the softer photon is still maintained

Replace cut on leading photon → cut on product of photon p_t's



$$f(p_{t,\mathrm{H}}) = f_0 + f_2\left(\frac{p_{t,\mathrm{H}}}{m_\mathrm{H}}\right)^2 + \mathcal{O}\left(\frac{p_{t,\mathrm{H}}^2}{m_\mathrm{H}^2}\right)$$

linear → quadratic

$$\frac{(2n)!}{2(n!)}\left(\frac{2C_A\alpha_s}{\pi}\right)^n \rightarrow \frac{1}{4^n}\frac{(2n)!}{4(n!)}\left(\frac{2C_A\alpha_s}{\pi}\right)^n$$

Using product cuts dampens the factorial divergence

NB: the cut on the softer photon is still maintained

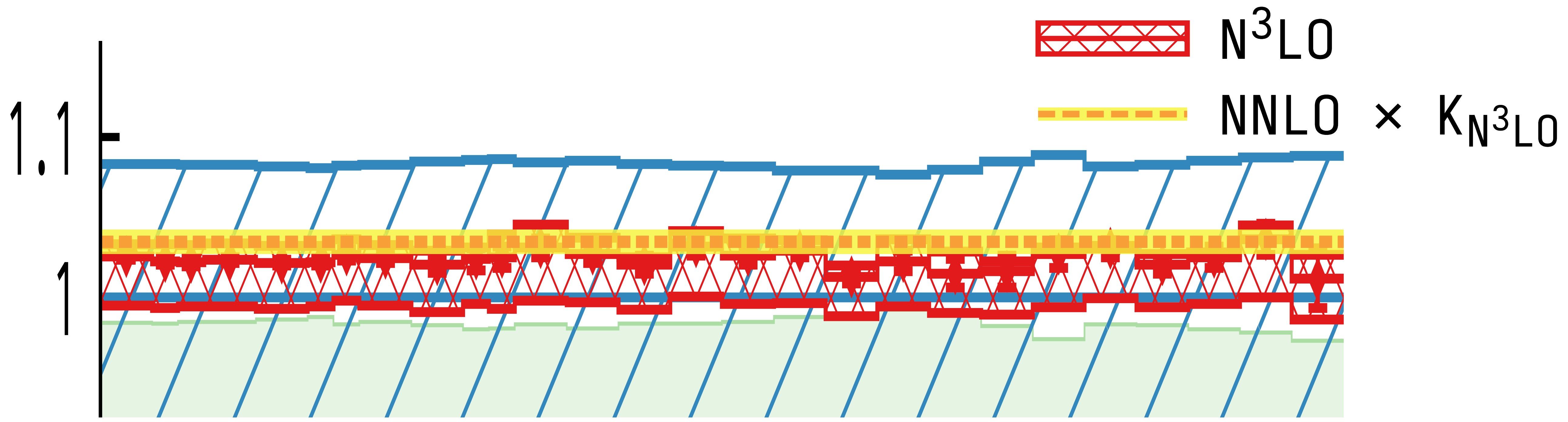
Behaviour of perturbative series with product cuts

$$\frac{\sigma_{\text{prod}} - f_0\sigma_{\text{inc}}}{\sigma_0 f_0} \simeq 0.005_{\alpha_s} - 0.002_{\alpha_s^2} + 0.002_{\alpha_s^3} - 0.001_{\alpha_s^4} + 0.001_{\alpha_s^5} + \ldots \simeq 0.003 \quad @\text{DL},$$
$$\simeq 0.005_{\alpha_s} - 0.002_{\alpha_s^2} + 0.000_{\alpha_s^3} - 0.000_{\alpha_s^4} + 0.000_{\alpha_s^5} + \ldots \simeq 0.003 \quad @\text{LL},$$
$$\simeq 0.005_{\alpha_s} + 0.002_{\alpha_s^2} - 0.001_{\alpha_s^3} + \ldots \simeq 0.005 \quad @\text{NNLL},$$
$$\simeq 0.005_{\alpha_s} + 0.002_{\alpha_s^2} - 0.001_{\alpha_s^3} + \ldots \simeq 0.006 \quad @\text{N3LL}.$$

Resummed results

Thanks to Pier Monni & RadISH for supplying NN(N)LL distributions & expansions, $\mu = m_H/2$

- Factorial growth of series strongly suppressed
- **N3LO truncation agrees well with all-order result**
- Per mil agreement between fixed-order and resummation **gives confidence that all is under control**



Huss et al preliminary @ Higgs 2021

Cuts & N3LO fiducial DY cross sections

Same conceptual problem for DY, but reduced because of C_F instead of C_A colour factor

Magnitude of problem can be estimated from difference between fixed order and fixed-order + resummation (recall: resummation should not be needed for a fiducial cross section)

Order	σ [pb] Symmetric cuts		σ [pb] Product cuts	
k	N^{k}LO	N^{k}LO+N^{k}LL	N^{k}LO	N^{k}LO+N^{k}LL
0	$721.16^{+12.2\%}_{-13.2\%}$	—	$721.16^{+12.2\%}_{-13.2\%}$	—
1	$742.80(1)^{+2.7\%}_{-3.9\%}$	$748.58(3)^{+3.1\%}_{-10.2\%}$	$832.22(1)^{+2.7\%}_{-4.5\%}$	$831.91(2)^{+2.7\%}_{-10.4\%}$
2	$741.59(8)^{+0.42\%}_{-0.71\%}$	$740.75(5)^{+1.15\%}_{-2.66\%}$	$831.32(3)^{+0.59\%}_{-0.96\%}$	$830.98(4)^{+0.74\%}_{-2.73\%}$
3	$722.9(1.1)^{+0.68\%}_{-1.09\%} \pm 0.9$	$726.2(1.1)^{+1.07\%}_{-0.77\%}$	$816.8(1.1)^{+0.45\%}_{-0.73\%} \pm 0.8$	$816.6(1.1)^{+0.87\%}_{-0.69\%}$

0.5% difference (symmetric cuts) — **no difference** (product cuts)

Chen, Gehrmann, Glover, Huss & Monni, 2203.01565

non-pert corrections & PDFs?

$$\sigma = \sum_{i,j} \int dx_1 dx_2 f_{i/p}(x_1) f_{j/p}(x_2) \hat{\sigma}(x_1 x_2 s) \times [1 + \mathcal{O}(\Lambda/M)^p]$$

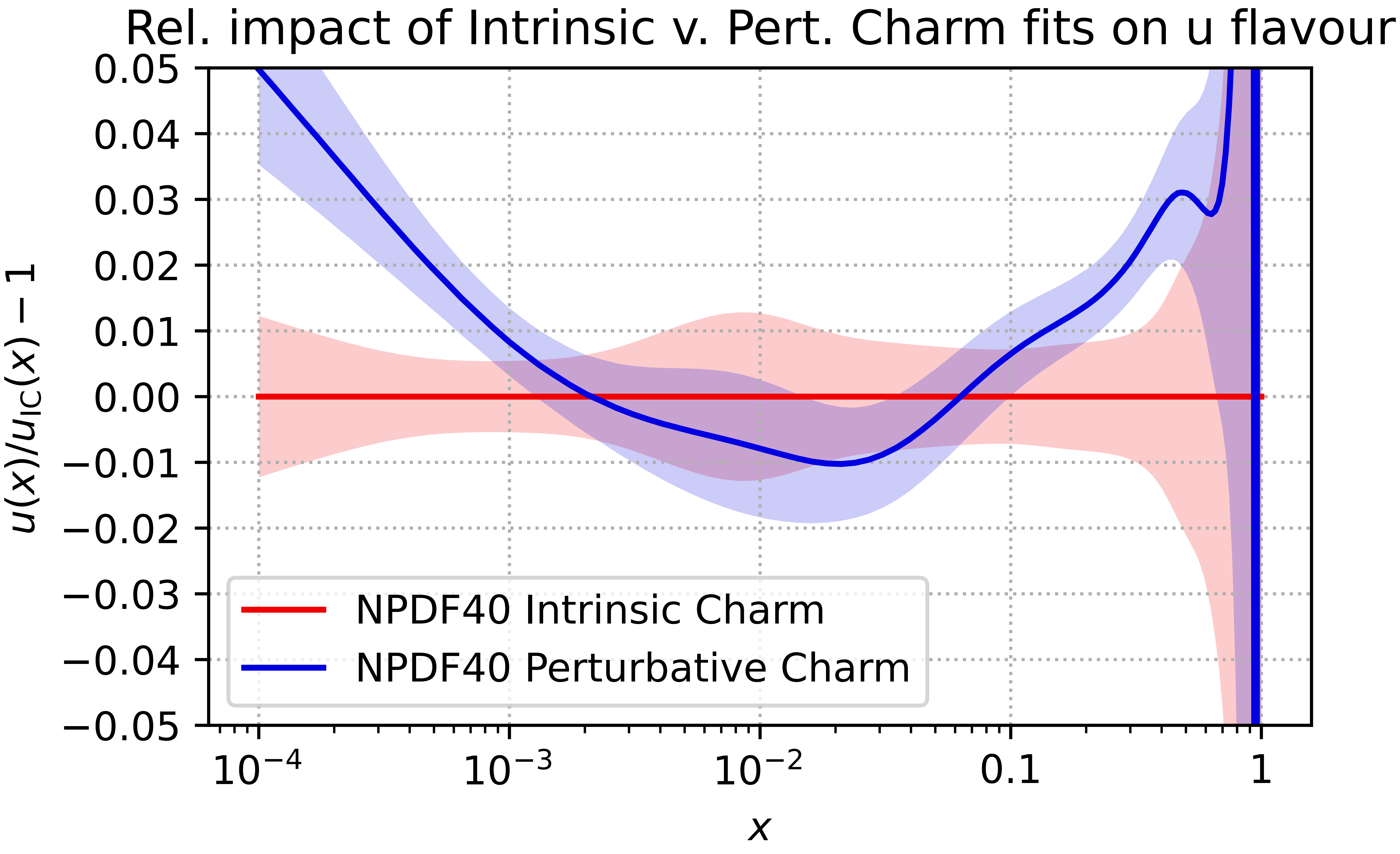
NNPDF4.0 DIS struct. fn. datasets [2109.02653] — all involve Λ^2/Q^2

Dataset	Ref.	$N_{\rm dat}$	x	Q [GeV]	Theory
NMC F_2^d/F_2^p	[33]	260 (121/121)	[0.012, 0.680]	[2.1, 10.]	APFEL
NMC $\sigma^{\rm NC,p}$	[34]	292 (204/204)	[0.012, 0.500]	[1.8, 7.9]	APFEL
SLAC F_2^p	[35]	211 (33/33)	[0.140, 0.550]	[1.9, 4.4]	APFEL
SLAC F_2^d	[35]	211 (34/34)	[0.140, 0.550]	[1.9, 4.4]	APFEL
BCDMS F_2^p	[36]	351 (333/333)	[0.070, 0.750]	[2.7, 15.]	APFEL
BCDMS F_2^d	[36]	254 (248/248)	[0.070, 0.750]	[2.7, 15.]	APFEL
CHORUS σ_{CC}^{ν}	[37]	607 (416/416)	[0.045, 0.650]	[1.9, 9.8]	APFEL
CHORUS $\sigma_{CC}^{\bar\nu}$	[37]	607 (416/416)	[0.045, 0.650]	[1.9, 9.8]	APFEL
NuTeV σ_{CC}^{ν} (dimuon)	[38, 39]	45 (39/39)	[0.020, 0.330]	[2.0, 11.]	APFEL+NNLO
NuTeV $\sigma_{CC}^{\bar\nu}$ (dimuon)	[38, 39]	45 (36/37)	[0.020, 0.210]	[1.9, 8.3]	APFEL+NNLO
[NOMAD $\mathcal{R}_{\mu\mu}(E_\nu)$] **(*)**	[111]	15 (—/15)	[0.030, 0.640]	[1.0, 28.]	APFEL+NNLO
[EMC F_2^c]	[44]	21 (—/16)	[0.014, 0.440]	[2.1, 8.8]	APFEL
HERA I+II $\sigma_{\rm NC,CC}^{p}$	[40]	1306 (1011/1145)	[$4\cdot10^{-5}$, 0.65]	[1.87, 223]	APFEL
HERA I+II $\sigma_{\rm NC}^{c}$ **(*)**	[145]	52 (—/37)	[$7\cdot10^{-5}$, 0.05]	[2.2, 45]	APFEL
HERA I+II $\sigma_{\rm NC}^{b}$ **(*)**	[145]	27 (26/26)	[$2\cdot10^{-4}$, 0.50]	[2.2, 45]	APFEL

~ 2 GeV

Table 2.1. The DIS datasets analyzed in the NNPDF4.0 PDF determination. For each of them we indicate the name of the dataset used throughout this paper, the corresponding reference, the number of data points in the NLO/NNLO fits before (and after) kinematic cuts (see Sect. 4), the kinematic coverage in the relevant variables after cuts, and the codes used to compute the corresponding predictions. Datasets not previously considered in NNPDF3.1 are indicated with an asterisk. Datasets not included in the baseline determination are indicated in square brackets. The Q coverage indicated for NOMAD is to be interpreted as an integration range (see text).

Intrinsic v. perturbative charm ~ Λ^2/Q^2 effect for $Q=m_c$



intrinsic charm v. perturbative charm fits are like including a Λ^2/Q^2 effect in the fit

Doesn't just affect charm PDF, but, e.g. also up-quark PDF

Raises question of more general Λ^2/Q^2 effects in PDF fits at level of few-% accuracy

Jet data has Λ/Q corrections — a concern for p_T cuts of 5 – 10 GeV

Dataset	Ref.	$N_{\rm dat}$	Q^2 [GeV^2]	p_T [GeV]	Theory
[ZEUS 820 (HQ) (1j)] **(*)**	[112]	30 (—/30)	[125,10000]	[8,100]	NNLOjet
[ZEUS 920 (HQ) (1j)] **(*)**	[113]	30 (—/30)	[125,10000]	[8,100]	NNLOjet
[H1 (LQ) (1j)] **(*)**	[115]	48 (—/48)	[5.5,80]	[4.5,50]	NNLOjet
[H1 (HQ) (1j)] **(*)**	[116]	24 (—/24)	[150,15000]	[5,50]	NNLOjet
[ZEUS 920 (HQ) (2j)] **(*)**	[114]	22 (—/22)	[125,20000]	[8,60]	NNLOjet
[H1 (LQ) (2j)] **(*)**	[115]	48 (—/48)	[5.5,80]	[5,50]	NNLOjet
[H1 (HQ) (2j)] **(*)**	[116]	24 (—/24)	[150,15000]	[7,50]	NNLOjet

Table 2.2. Same as Table 2.1 for DIS jet data.

conclusions

Concluding message

For many parts of the field there is a clear path forward on precision

But we are reaching the point where we also need to reconsider the heuristics that get adopted for the $(\Lambda/Q)^p$ terms

backup